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CANADA/NB MDA PROJECT ON MINE-SHAFT ROPE TESTING; STRANDED ROPES WITH ARTIFICIAL DEFECTS

L.B. GELLER, G. ROUSSEAU AND D. POFFENROTH

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CANADA/NB MDA PROJECT ON MINE-SHAFT ROPE TESTING; STRANDED ROPES WITH ARTICIAL DEFECTS

by

L.B. Geller*, G. Rousseau**, and D. Poffenroth†

ABSTRACT

Contracted work was undertaken, funded from Canada/New Brunswick Mineral Development Agreement (MDA) sources. Begun in July, 1988, its principal objective was to comparatively evaluate, on a properly controlled experimental basis, the performance of a range of commercially available electro-magnetic (EM) wire-rope test instruments, including Canadian, American, and West German testers. Both in situ and shop-floor testing was performed, on rope-sizes and constructions that are representative of the full range used in Canadian mines. Results were obtained in close cooperation with Canadian regulatory authorities, research organizations, and industry. Moreover, our US colleagues at their Bureu of Mines and at their Mine Safety and Health Administration (MSHA), as well as scientists from a major West German rope testing laboratory (the WBK), also collaborated.

In this report we describe and analyse results that were obtained with one of the many rope-sets examined during the course of the CANMET project in question. Specifically, we deal with the reel-to-reel testing of two specially designed and manufactured $1\frac{3}{4}$ in., 6×27, flattened strand, wire-ropes, with artificial defects.

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Keywords: New Brunswick; Mineral Development Agreement; wire-ropes; non-destructive-testing; electro-magnetic instruments; stranded ropes

RÉSUMÉ

PROJECT DE L'EEM CANADA/N.B. SUR L'ESSAI DE CÂBLES POUR PUITS DE MINE; CÂBLES TORONNÉS AVEC DÉFAUTS ARTIFICIELS

par

L.B. Geller*, G. Rousseau**, et D. Poffenroth†

Des travaux contractuels ont été entrepris lors d'un project financé par le Canada-Nouveau Brunswick l'entente sur le développement minéral. Débutant en juillet 1988, son principal objectif est l'évaluation comparative, dans des conditions expérimentales contrôlées, des performances d'une gamme d'instruments électromagnétiques commerciaux servant à tester les câbles d'acier. La gamme couvre des instruments canadiens, américain et allemand. Des tests en atelier et in situ ont été réalisés sur des câbles de dimension et de construction représentatives de celles en usage dans les mines canadiennes. Les travaux ont été réalisés en étroite collaboration avec les représentants des bureaux gouvernementaux, des organisations de recherche et de l'industrie. De plus, nos collègues américains du Bureau des mines et du Bureau de la santé et de la sécurité minière, ainsi que des scientifiques d'un important laboratoire de câbles situé en Allemagne ont collaboré à ces travaux.

Dans ce rapport les auteurs décrivent et analysent les résultats obtenus en atelier avec deux câbles spécialement conçus et fabriqués pour les fins de ce projet. Les câbles torronnés, testés de bobine à bobine, sont de construction $1\frac{3}{4}$ po, 6×27, et ils contiennent des défauts artificiels introduits lors de l'étape de fermeture du câble.

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Mots clés: Nouveau-Brunswick; Entente sur l'exploitation minérale; câbles, essai non destructif, instruments électromagnétiques; câbles torronnés

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2	%LMA in-between major defect sections
3	%LMA at core sections containing loose metal
4	shift of 0% LMA ref. line along defective rope section

Test-rope 'B'	
Table No.	Table content:
5	%LMA in major defect sections B15, B13, B12, B9, and B6
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Test-rope 'A'					
Instrument:	Test-date:	Chart-speed:	Report Figure No.		
			A^*	B^{**}	C^{***}
Rotescograph	April, 1989	5 mm/sec	1a	16	23a; 23b; 23c; 24a; 24b; 24c;
		1 mm/sec	1b		
		0.5 mm/sec	1c		
LMA-250	April, 1989	5 mm/sec	3	17	23a; 23b; 23c; 25a; 25b; 25c;
	March, 1990	5 mm/sec	5	18	25a; 25b; 25c;
Magnograph	April, 1989	5 mm/sec	$7b_1$	15	24a; 24b; 24c; 26;
		0.5 mm/sec	$7b_2$		
		FAX'd	7a		
	March, 1990	1 mm/sec	9b	20	26
		0.5 mm/sec	9a		

Test-rope 'B'					
Instrument:	Test-date:	Chart-speed:	Report Figure No.		
			A^*	B^{**}	$C^{\dagger}$
Rotescograph	April, 1989	5 mm/sec	2a	11	27a; 27b; 27c;
		1 mm/sec	2b		
		0.5 mm/sec	2c		
LMA-250	April, 1989	5 mm/sec	4a (2nd run)	13	27a; 27b; 27c; 29a; 29b;
		5 mm/sec	4b (1st run)		
	March, 1990	5 mm/sec	6	14	29a; 29b;
Magnograph	April, 1989	5 mm/sec	$8b_1$	12	27a; 27b; 27c; 28;
		0.5 mm/sec	$8b_2$		
		FAX'd	8a		
	March, 1990	1 mm/sec	10b	19b	28
		0.5 mm/sec	10a	19a	

*: charts illustrate total rope-lengths

**: charts illustrate mapped rope-sections

***: charts illustrate enlarged defect-sections A16, A14, A13, A10, A9, and A6

†: charts illustrate enlarged defect-sections B15, B13, B12, and B9

BACKGROUND

Non-destructive testing (NDT) of mine-shaft wire-ropes with electro-magnetic (EM) instruments is a universally practiced, and well established technique of great practical value. Even so, results obtained with these testers still do not achieve the benchmark level of accuracy set for them — as an example by Ontario's "Performance Requirements for EM Testers". This fact has been extensively documented, and the underlying reasons analysed, in three previous CANMET reports (1, 2, 3). The results discussed in these reports are based, primarily, on an examination of a uniquely extensive list of destructive and non-destructive experiments, obtained at the Rope Testing Laboratory of the Ontario Ministry of Labour. In addition, these reports also contain an examination of the Canadian regulatory requirements dealing: (a) with the mine-shaft ropes' discard criteria, and (b) with the question of approval, of both the EM instruments and of their operators. In addition, the reports contain a listing of the rope-sizes and constructions used, as of December, 1987, in most Canadian mine-shafts.

In the present report we describe, and analyse, some of the test results that were obtained during CANMET's contracted project-work. Specifically, we deal with the shop-floor results obtained with the $1\frac{3}{4}$ in., 6×27, flattened-strand, wire-ropes with artificial defects, that were specially designed and manufactured for this project. These ropes were tested with two Canadian, one American, and one West German EM instrument.

TEST-ROPE CONSTRUCTION

The specially designed and manufactured test-ropes, involved in the work we describe in this report, are of $1\frac{3}{4}$ in. nominal size, 6×27, F.S., fibre-core construction, with a nominal breaking-strength of 306,000 lb, a total metallic cross sectional area (A) of 1.399 in^2, and a lay-length of 13.2 in. Each strand contains twelve 0.123 in. diam outer-wires (each representing some 0.86% of A), and twelve 0.074 in. diam inner-wires (each representing some 0.31% of A). In each strand there are also three 0.118 in. diam centre- and three 0.036 in. diam filler-wires. The latter represent some 0.80% and 0.07% of A, respectively.

The artificial defects include Loss-of-Metallic-Area (LMA), Local-Faults (LF), and Trapped Debris (TD).

The four major loss-of-metallic-area (LMA) sections were obtained by butt-welding 6 ft long sections of thinner wires to the regular sized outer/inner wires. At the locations marked: "*7.0% LMA (3 outer-wires)*", three of the twelve 0.123 in. outer-wires

were replaced by 0.091 in. wires. At the locations marked: "*7.2% LMA (12 inner-wires)*", all twelve of the twelve 0.074 in. inner-wires were replaced by 0.061 in. wires. At the locations marked: "*7.6% LMA (3 outer-wires)*", three of the twelve 0.123 in. outer-wires were replaced by 0.088 in. wires. At the locations marked: "*7.7% LMA (12 inner-wires)*", all twelve of the twelve 0.074 in. inner-wires were replaced by 0.060 in. wires.

To test the EM instruments' response to loose TD, the fibre core of each test-rope was replaced, at the locations indicated in the defect-mappings, by $\frac{3}{4}$ in. O.D. $\times$ $\frac{5}{8}$ in. I.D. plastic tubes, filled with TD as represented by: (a) iron filings, over a 6 ft length, (b) magnetite, over a 3 ft length, and (c) corrosion products, over a 6 ft length. The latter were scraped off the surface of an operational mine-shaft rope (rope #7 in Table 9 of MRL report #89-40). It will be noted that the $\frac{5}{8}$ in. I.D. represents some 21.9% of the 1.399 in^2 total metallic rope cross-section (A). Consequently, even if only 55% of this space is metallic material, the rope's metallic cross-sectional area is much increased. The chemical composition of the E-96 magnetite, and of the loose iron filings (codes MP-20 and MP-41), has been reported by others (see Appendix 1). These results are of little, if any, interest to us under the present circumstances. The magnetic properties of the TD are, however, of great importance. We measured these ourselves. The process used, and the results achieved, are described elsewhere (4).

LF defects consist of wire-breaks and of missing lengths of wire. Although every effort was made to map their nature and location within the rope accurately, this proved to be impossible because breaks occurred unintentionally at the individual wire butt-welds, during the actual rope manufacturing process. It follows, however, from the previously described method of constructing the LMA rope sections, that most of these unintentional wire-breaks are located at the extremities of the four major LMA sections. Moreover, in our view it also follows from CANMET's principal project objective that this relative uncertainty about the exact location and nature of the LF defects does not detract from the value of the test results achieved. This is so because, other than in case of a previous major effort to comparatively evaluate the LF signals of a range of EM instruments (5), our present goal is to establish the relative level of accuracy with which a range of commercially available EM instruments can be used for estimating loss-of-breaking-strength (LBS) values in mine-shaft wire-ropes. In this context we note that our situation does not materially differ from most operational conditions: there too the exact location and nature of the rope defects is often unknown.

As far as can be ascertained then at this point, the test-ropes' defect-mapping is as follows:

In case of test rope A

Location:	Type of defect:	Symbol:
0-24 ft	no defects	A1
at 24 ft	missing- and broken-wires (one outer, at least); wire-gap	A2
30-36 ft	7.0% LMA (3 outer wires)	A3
at 36 ft	broken outer-wire (one at least)	A4
at 42 ft	broken outer-wire (one at least)	A5
42-48 ft	7.6% LMA (3 outer wires)	A6
at 48 ft	broken outer- (four at least) and inner-wires (two at least)	A7
at 54 ft	broken outer- (one at least) and inner-wires (three at least)	A8
54-60 ft	7.2% LMA (12 inner wires)	A9
54-57 ft	magnetite for rope core	A10
63-69 ft	iron filings for rope core	A11
at 66 ft	broken inner-wire (one at least)	A12
66-69 ft	7.7% LMA (12 inner wires)	A13
69-72 ft	7.7% LMA (12 inner wires)	A14
at 72 ft	broken inner-wire (one at least)	A15
75-81 ft	corrosion products for rope core	A16
81-250 ft	no defects	A17

and in case of test rope B

Location:	Type of defect:	Symbol:
0-24 ft	no defects	B1
at 24 ft	missing- and broken-wires (two outer, at least); wire-gap	B2
30-36 ft	7.0% LMA (3 outer wires)	B3
at 36 ft	broken outer-wires (two at least)	B4
at 42 ft	broken outer-wires (three at least)	B5
42-48 ft	7.6% LMA (3 outer wires)	B6
at 48 ft	broken outer- (five at least) and inner-wires (two at least)	B7
at 54 ft	broken inner-wires (two at least)	B8
54-60 ft	7.2% LMA (12 inner wires)	B9
at 60 ft	broken inner-wires (four at least)	B10
beyond 60 ft	broken inner-wires (unknown number)	B11
66-69 ft	7.7% LMA (12 inner wires)	B12
69-72 ft	7.7% LMA (12 inner wires), and magnetite for rope core	B13
at 72 ft	broken inner-wires (four at least)	B14
78-84 ft	iron filings for rope core	B15

90-96 ft	corrosion products for rope core	B16
96-250 ft	no defects	B17

In view of the inaccuracy of the distances recorded on the various instrument charts, the footages listed above can not be used otherwise than as an approximate guide for locating the artificial defects. Also, some of the test runs commenced at one end of these ropes, and others at the other end. Consequently, to avoid ambiguity, we elected to refer to the defect-groups by the symbols A1, A2, etc.

EM TESTING OF ROPES — GENERAL PROCEDURE

The two $1\frac{3}{4}$ in. $\times$ 250 ft long stranded test-ropes in question were joined together by welding lugs to each of their ends, and then by stringing smaller diameter cables between them; several hundred-ft lengths of lead-cable also preceded and followed the 500 ft test rope stretch. The entire assembly was mounted on a pay-out reel, and uncoiled onto a rope-winder mounted take-up reel. Braking of the pay-out reel provided the only means of rope tensioning. Rope speeds were not too steady, varying from about 40 to 100 ft/min. Stoppages also arose, not infrequently.

The Canadian Rotesco AC instrument was not available to us at the time we shop-floor tested the stranded ropes in question. However, the rope assembly was passed through several other EM testers, of permanent-magnet design. These were placed in series, one behind the other, on a wooden table. The instruments were aligned after their magnetic polarities had been carefully checked to prevent any one field from interfering with another. Altogether two Canadian (the Magnograph and Rotescograph), one American (the LMA Series 250) and a West German (designed by WBK) instrument were used. All had been maintained and calibrated, on a regular basis, either by the instrument makers themselves, or by the operators. The latter were known to, and approved by, the instrument makers/designers.

The Rotescograph was handled by its regular operator, a staff member of the instrument's owner (a major Canadian mining organization). The Magnograph was also operated by its owner (a service company). The LMA-250 was handled by its regular operator, an engineer from a cooperating US Government organization; he has had an exceptional amount of both theoretical and practical experience in operating several types of EM wire-rope testers. The WBK instrument was handled by a team of two scientists from Germany. Their organization had designed the EM tester in question. All operators have had extensive field, and in some cases also laboratory, experience in taking measurements.

As may be seen, our project involves an international cooperative effort, with a representative range of test-instruments. Thus, the results achieved represent the combined input, both technical and financial, of several organizations. The North-American instruments are commercially available models. The German tester is a recently developed prototype. It is understood that it will eventually be made commercially available. Measurements were obtained completely independently; the reports too were submitted to CANMET without any of the teams being aware of each other's results. Moreover, the instrument operators only knew about the rope construction details, but nothing about the nature or location of the artificial defects. Everyone had the opportunity to test each of the test ropes at least twice, in some cases even more often. Consequently, the operators were given the opportunity to rectify any unforeseen problems caused by inappropriate instrument calibration or gain settings.

The aforementioned general test-procedure is illustrated by a series of photographs (Figures 36 to 55), contained in Appendix 4 of this report. A VCR record was also prepared of our shop-floor work.

INSTRUMENT CHARACTERISTICS

As mentioned above we used four instruments for testing the test-ropes with artificial defects. Three of these, namely the Rotescograph, LMA-250, and the German WBK design, constitute one major group, characterized by the use of sensing coils for detecting the leakage flux developed by local rope-defects. The Magnograph is different, insofar as it uses Hall sensors for generating both its LMA and LF signals. This design difference results in a number of different basic instrument characteristics of practical consequence. It is not, however, our purpose to discuss, in any great detail, the intricacies of different designs. This has been done elsewhere, e.g., by Rieger and Feyrer (7, 8). Instead we propose to concentrate on the practical aspects that are of primary concern to those who use these EM testers. It is with this in mind that we assembled the following list, not in any order of relative importance, of desirable instrument characteristics. In our opinion this list contains the salient characteristics that: (a) potential users might wish to first check-out with their prospective suppliers, and (b) will assist those who need to evaluate test-results in order to be in a position to draw important conclusions for future action.

Desirable instrument characteristics:

(1) the instrument should be designed for adding, if so desired, electronic means to the paper-chart records — such as, for example, a frequency modulated (FM) tape recorder — for recording, and for faithful play-back, of the following signals:

(a) LMA, (b) LF, (c) test-speed, (d) length, and (e) direction of measurements. The signal-to-noise ratio of the recording and play-back process should be kept as high as possible, in order that: (a) the added noise be less than 0.1% on the LMA channel, and (b) the LF signal induced by a rope-defect not be lost among the electronic noise. Our present report illustrates how useful the availability of such electronic means is;

(2) all control settings, such as zero and gain for both the LMA and LF signals, should be equipped with a dial both readable, as well as resetable, to within $\frac{1}{10}th$ of 1.0%, so as to be able to exactly reconstruct the levels set during the original rope tests;

(3) the electronic and magnetic characteristics of the test instrument must be stable time-wise (say at least between factory calibrations) and temperature-wise (say between -20 deg C and +40 deg C for the sensor-head, and between +5 deg C and +35 deg C for the electronics);

(4) the instrument's speed-compensation must ensure that the amplitude of a discontinuity will remain constant regardless of rope speed;

(5) both LF and LMA measurements should be independent of rope speeds in the approximate range of zero to 600 ft/min;

(6) the instrument should produce charts with both LMA and LF traces. The charts appended to this report (Appendix 3), as well as conclusions published in other CANMET reports (1, 2, 3), provide ample evidence to support this contention. We use the terms: (a) LMA trace as meaning a quantitative measure of the magnetizable mass, either in relative or in absolute terms, and (b) LF trace as meaning the production of a trace able to detect the presence of a small leakage flux, developed by local discontinuities in the wire-ropes;

(7) the instrument's LMA, LF, distance, and direction signals should be easily accessible for further recording or processing;

(8) the range of the LMA measurements should extend to at least +5.0% and -20.0%, in case of the largest rope-size measurable by the given instrument;

(9) the instrument's chart-paper advance should be proportional to the measured rope-length;

(10) the instrument should be capable of both absolute and relative metallic-area measurements;

(11) it should be possible to locate the sensor-head at least 25 ft from the control unit;

(12) influence of outside electro-magnetic fields upon the instrument's output signals should be within acceptable limits;

(13) the auxiliary magnetic field induced by the sensor-head should be minimized;

(14) the instrument should be easily portable; be capable of self-contained operation, its batteries should last for at least six hours of continuous operation; it should be sturdy and resistant to environmental effects (e.g., it should be splash-proof); and it should have mounted on it, at an appropriate location, condensed intrument operating instructions and chart calibration procedures;

(15) a warning signal must appear whenever the instrument's electronic circuit reaches saturation, i.e., whenever the data produced have been rendered invalid;

(16) instrument stability should be within 1.0% LMA per hour — as an example a 10.0% LMA should not drop to less than 9.0% within an hour. In this context we refer to our discussion of the instrument stability problems elsewhere in this report.

TEST RESULTS — AN OVERVIEW

Although CANMET's Work Statement for the contracted project specified that all NDT reports had to include the estimated Loss-of-Breaking-Strength (LBS) values — besides a listing of the observed Local-Faults (LF) and Loss-of-Metallic-Areas (LMA) — some instrument operators only agreed to provide the latter two values. Consequently, our overall analysis deals only with the LMA and LF values obtained. Unfortunately, we had not been given copies of the German test results at the time of writing this report. We plan to publish these separately later, as soon as we obtain them.

We consider it both unnecessary and unhelpful to include in this report our step-by-step analysis of all the available test charts. Detailed evaluation of a few charts is, however, appended (Appendix 2). In Appendix 3 we are also providing summary listings (Tables 1 to 8) of all relevant results. The tabulated LMA figures are indicated values, read directly from the relevant strip-charts. Moreover, copies of all charts are appended (Appendix 3). Readers will, therefore, be able to arrive at their own conclusions as to the quality of the various instrument traces. As to the accuracy of the results (Tables 1 to 8), we make the following general comments:

(1) <u>the reported LBS estimates</u>: we do not include the operators' analyses in this report because: (a) not every operator agreed to supply these, and (b) at this

point we can not sacrifice our expensive test ropes by having sections destructively tested. Consequently we are unable to verify the accuracy of the reported LBS data. We shall discuss the problem of how to estimate the respective LBS data in a subsequent CANMET report;

(2) the LF defects: in view of the uncertainty regarding the exact location and character of these faults, there is no point in quoting the operators' chart-analyses as to the nature of the artificial rope-defects. On comparing, however, the various instrument charts, it will be seen that all LF traces recorded the *de facto* situation clearly and consistently. Only ultimate verification of the chart interpretations remains in some doubt;

(3) the LMA defects: as with the LF chart traces, qualitatively all charts are clear and consistent enough. However, the reported quantitative results (Tables 1 to 8) differ by a wider margin than we consider to be "acceptable". We are not aware of benchmark values having been established in any Code of Practice for an "acceptable" LMA measuring range, similar to the ±4.0% range established by Ontario's "Performance Requirements for EM Testers" (1) for the LBS measurements. We suggest, however, that ±2% could be such a benchmark value for the LMA data because: (a) our own data in Tables 1 and 5 established this to be a practical range that can accomodate the accuracy limitations due to the physical instrument characteristics, in other words this range has been shown to be neither unrealistically restrictive, nor too lax, (b) others (6) have also stated that "in view of the fact that measurement is affected by the attributes of the rope (magnetization curve of the rope material, tension, length of lay), and calibration curves, measurement standards should achieve an accuracy of about ±2% of the cross-section of the rope", (c) the operators of the German WBk instrument previously undertook a series of their own experiments and found that, with their tester, the average discrepancy between "true" and measured metallic cross-sectional rope areas was in the order of 0.5% to 1.0%, and (d) it should be possible to achieve the desired ±4% LBS "acceptability" restriction, as long as the LMA accuracy is kept within ±2%. We tacitly assume here the adequacy of the present (or future) algorithm for converting LMA and LF measurements into LBS results, a problem we plan to address in a future CANMET report.

The obvious differences in the LMA results are, in our opinion, primarily due to human factors, and not to hardware related matters. Some questions do, however, arise in relation to the latter as well, in particular the shifting of the LMA trace after passing over the artificial defects, and the possibility of electronic circuit saturation. We shall discuss the latter phenomenon in a future CANMET report on "Absolute LMA

measurements". As for the human factors in question, these include: (a) improper setting of the 100% LMA-chart reference levels, and (b) improper instrument calibration and gain setting procedures.

In the four major LMA rope sections (Tables 1 and 5) the "true" LMA values are based on the known metallic rope area reductions, described in an earlier section of this report. In case of the sections with metal powders in the rope cores, the "true" LMA values (Tables 3 and 7) are based on the considerations — such as a 55% fill-factor — described elsewhere (4).

The principal test-results are summarized in Appendix 3 (Tables 1 to 8, and Figures 1 to 29). Our general comments regarding the results are as follows:

(1) for a proper evaluation of the EM charts, the LMA and LF traces must be considered in conjunction. Also, under normal operating conditions, instrument charts must not be evaluated in isolation. Instead this should be done in full knowledge of the results obtained on the same rope by all previous EM tests. If possible, complete NDT documentation of the companion ropes should also be obtained;

(2) regarding the charts in Appendix 3: Figures 1 to 10 are copies of the entire chart-lengths, while Figures 11 to 20 are copies of only partial lengths of the same charts, but with added mappings of: (a) the locations, and (b) the magnitudes of the major artificial defects. In both groups of figures we drew-in the zero % LMA-loss — i.e., the 100% metallic area (M.A.) — reference levels. We also provided match-marks (such as ref. 'A'; ref. 'B'; etc.) wherever we were unable to copy the entire chart-lengths in a single stretch.

Another group of figures (numbers 23 to 29) is also provided, to more clearly illustrate the characteristic chart-features, and the repeatability of our measurements. Such a large number of charts is provided in order to amply illustrate two major aspects: (a) repeatability, and (b) the use of electronic back-up records;

(3) On comparing the %LMA values read off the charts with the "true" ones for the rope sections with major defects (Tables 1 and 5), we note that, on the whole:

(a) the Rotescograph results are the least accurate;

(b) Rotescograph %LMA results are less than the "true" values;

(c) we cannot say why the foregoing should be so. We can only speculate that the reasons are related to the calibration/gain settings used, and/or to some specific test instrument/recorder package related circumstances;

(d) the Magnograph and the LMA-250 results are sometimes less, sometimes more than, and sometimes equal to the "true" values. Their ±2% accuracy range is "acceptable";

(e) with all three instruments, the chart-data for the artificial defect A9 (see Table 1) are widest of the mark, and always well below the "true" value. We cannot say exactly why this should be so, other than to point to the general uncertainty caused by having in this rope section overlapping defect-groups;

(f) it is unclear why the %LMA values in-between the major defect sections (see Tables 2 and 6) should, more often than not, be other than the 0.0% that we expected. Again we can only surmize that this is due, at least to some extent: (1) to the problem of correctly setting the 0.0% LMA-loss reference line, (2) to difficulties in the preparation of the test-ropes, that resulted in both distortions, variations in lay-lengths, and uncertainty as to the exact location and magnitude of some defects, and (3) to overlapping of magnetic-fields caused by the various closely spaced defect-groups;

(g) on the basis of our test results the bench-mark range for "acceptable" %LMA measurements with EM instruments can be set at ±2.0%;

(4) in many cases it is unclear exactly why the 0.0% LMA-loss reference line should have shifted along the defective rope section (see Tables 4 and 8). Our thoughts on this subject are contained in the report section on "instrument stability";

(5) the repeatability of these EM tests has been amply demonstrated by tabulating the results obtained: (a) with the Rotescograph on three different occasions, each several days apart, and (b) in case of the LMA-250 and the Magnograph on occasions that were from hours (see Figures 4a and 4b) to almost a full year apart. In the latter case see Figures 3 vs 5 and Figures 4a vs 6 for the LMA-250, and Figures $7b_1$ vs 9a plus Figures $8b_1$ vs 10a for the Magnograph. The repeatability of both the LMA and LF chart-traces is noteworthy. We discuss further details of this aspect in the report section on "repeatability".

SOME POINTS OF SPECIAL INTEREST

Instrument stability

We append to this report (Appendix 3) copies of the entire instrument chart-lenghts (Figures 1 to 10) so as to illustrate how stable the 100% metallic-area (M.A.) reference level (i.e., the 0.0% LMA-loss level) remains along the non-defective rope

lengths, and how it shifts along the defective rope-sections. Match-marks are provided (such as ref. 'A'; ref. 'B'; etc.) wherever we were unable to copy the entire chart-lengths in a single stretch. The salient quantitative %LMA values, as read off these charts, are listed in Tables 1 to 8. The amount of 100% reference level shift is recorded in Tables 4 and 8.

In case of the NDT Technologies' LMA-250 instrument, its design includes a zero-seeking integrator device. Following our April, 1989, shop-floor test series, we conducted laboratory tests to determine the effect of the zero-seeking integrator, i.e., of the effect often referred to as the "drooping" of the LMA signal. This phenomenon arises whenever a decrease or increase of metal in the wire-rope causes a positive or negative voltage, with respect to zero, and thereby activates the zero seeking integrator, which then causes the voltage to migrate back to zero at a certain design rate.

After setting the strip-chart gain at 50 mV/mm, and the chart-paper speed at 25 mm/min, we undertook the test-procedure, and obtained the test-results, summarized in Table 9 (Appendix 3).

The test-results indicated the following:

(1) for any given LMA-gain potentiometer setting, the migration back to zero is, for practical purposes, linear;

(2) the higher the LMA-gain potentiometer setting, the faster the migration. Consequently, the zero migration is more of a problem in case of small diameter ropes, rather than large diameter ones, because the LMA-gain potentiometer settings are higher in the former case. However, in case of certain types of rope defects, zero-migration can be a problem for any rope diameter, if the rope is a long one (say a few thousand feet);

(3) for a given LMA-gain potentiometer setting, the negative migration to zero is at a higher rate than is the positive migration to zero (note test #3 vs test #4);

(4) the instrument senses the change in metallic area due to insertion, or removal, of the strand, up to the saturation limit of the electronic integrator circuit. The presence of an additional, unchanging, metallic mass is immaterial, as long as the unchanging metallic mass is magnetically saturated (note test #4 vs test #5).

Following the April, 1989, shop-floor test series, and prior to our March, 1990, tests, the LMA-250 instrument's electronic control unit was modified by the manufacturer. Following our 1990 tests we, therefore, repeated our droop tests with the LMA-250 tester. This time chart speed was set at 5 mm/sec, and the LMA sensitivity

at 20 mV/mm. Two three-ft long rods, with a total metallic area of 1.32 in^2 were used to simulate the $1\frac{3}{4}$ in. test ropes 'A' and 'B'. In case of droop-test #1 a third, smaller, rod was inserted alongside the "rope", to simulate a positive anomaly. The resulting "droop" (Fig. 21a) was –0.117% per min. In case of droop-test #2 the smaller rod was removed from alongside the "rope", to simulate a negative anomaly. The resulting "droop" (Fig. 21b) was +0.075% per min. Repeat tests with a digital Volt-meter and a stop-watch resulted in almost identical results: +0.08% per min and –0.14% per min, for rod removal and insertion, respectively. To obtain the improvement in the "droop" rate due to the manufacturer's modifications: compare the latter data with the ones listed in Table 9 (Appendix 3).

The 1990 experimental "droop" values (Fig. 21) can also be compared with the –0.5% and –0.8% droops (Figures 5 and 6), listed in Tables 4 and 8 for the March 6, 1990, ropes 'A' and 'B' tests with the LMA-250. In this case our strip-chart speed was 5 mm/sec. The recorded anomalies (mostly negative ones) occurred over a rope length of some 60 ft, at a rope speed of about 40 ft/min, i.e., over about a 90 sec time period. This would result in a calculated "droop" of some +0.12% and –0.21%, respectively.

Finally, we wish to record the most recent droop-test (#3) results, as reported to us by the instrument's (the LMA-250) manufacturer (Fig. 21c). The test was performed with a new signal-box. It is also reported that the experiment corresponds to a 2 in. rope, with a 9.5% LMA, and that the lock-range setting was 0.3 (out of 10.0 full-scale). The LMA-scale (Fig. 21c.) is 0.5% LMA per mm (i.e., per minor chart division), and the time-scale approximately 1.02 min per major chart-division. The reported results demonstrate that the droop-rate can be reduced to less than 0.5% LMA/hr, i.e., to well within the accuracy limits of the EM inspection method. In this context it may also be said that the droop is only significant for long ropes which have deteriorated over a considerable length, especially if this deterioration is gradual, say wear rather than wire-breaks. Otherwise, the droop may become negligible, because the instrument gradually resets itself whenever a rope section with 0% LMA is encountered.

In Tables 4 and 8 we also recorded shifting of the 100% M.A. reference level in case of the Rotescograph and the Magnograph traces. Neither of these two instruments include a zero-seeking integrator in their design; instead of a sensing coil, their LMA signals are generated by Flux Gate Sensors and with Hall Sensors, respectively. Consequently, the "droop" phenomenon, as such, does not apply to them. Our "droop" test results with the Magnograph are shown in Figures 22a and 22b. The recorded shifts (see Tables 4 and 8) are, indeed, negligible for the Magnograph in all cases. For the Rotescograph though the records of April 5 and April 15, 1989, include three charts (Figures 1b, 2a, and 2b) with reference level shifts of 1.0% and more. At this stage

we can only record this anomaly, without explaining its origin. Possibly test instrument/recorder package related circumstances, specific to the hardware used, are at the root of the problem. Attention is, all the same, drawn to our observations.

Setting of 100% reference level on the LMA chart

Figures 1 to 10, with copies of the entire chart-lengths, were referred to previously in the report section on "instrument stability". These figures (Appendix 3) also illustrate a related problem: the occasional difficulty of correctly setting the 100% M.A. (i.e., the 0.0% LMA-loss) reference level on the LMA chart traces. One such difficulty arose with the LMA-250's chart-trace of test-rope 'B' (Fig. 4a). The problem is discussed in Appendix 2. It was caused by a "hump" at the front-end of the LMA trace, which — unbeknown to the respective operators at testing time — showed up on the Rotescograph and Magnograph charts as well (see Figures 2a, 4a, and 8a).

Another situation of this kind, also referred to in Appendix 2, concerns the misplacement of the 100% reference level in case of the April 5, 1989, Rotescograph measurement of test-rope 'B' (Fig. 2a). Perhaps these two examples of misplaced reference levels illustrate more of the human involvement in the problem areas relating to EM testing than of the hardware related ones; however, if absolute, rather than relative, LMA measurements were to be obtained (a hardware related matter), the human involvement would be correspondingly reduced.

Repeatability

In Appendix 3 we append copies of a wide selection of instrument charts (Figures 1 to 20) that were obtained with a range of instruments under identical conditions. We do so in order to illustrate several important points related to EM testing of wire-ropes. These include: (1) the need to obtain the clearest possible chart-trace information, (2) the occasional problems caused by incorrect setting of the instrument-calibration values and chart recorder gains, (3) and the occasional problems caused by incorrectly setting the 0.0% LMA-loss reference levels. Repeatability is another important point.

As to repeatability. It will be noted that we append: (1) for the Rotescograph charts obtained on three different occasions, each several days apart (Figures 1a, 1b, and 1c for test-rope 'A', and Figures 2a, 2b, and 2c for rope 'B'), (2) for the Magnograph charts obtained almost a full year apart (Figures $7b_1$ and $8b_1$ vs Figures 9b and 10b), and (3) for the LMA-250 charts obtained from hours apart (Fig. 4a vs Fig. 4b) to almost a year apart (Fig. 3 vs Fig. 5 and Fig. 4a vs Fig. 6). The remarkable degree of

qualitative repeatability can be observed by studying (Appendix 3) the aforementioned Figures 1 to 10, their "mapped" equivalents (Figures 11 to 20), and Tables 1 to 8.

In addition, for test-rope 'A' we append Figures 23 to 26, and for rope 'B' Figures 27 to 29, showing enlarged details of the most characteristic chart features. As to the LMA traces in these figures: it is quite remarkable how clearly the salient features of each artificial defect group are repeated in all of these charts, for all instruments, irrespective of the time that may have elapsed between two related pairs of measurements.

As to the LF traces in the figures referred to. Here too the repeatability is quite remarkable. However, Figures 23 to 29 also illustrate another important instrument feature, namely the qualitative differences between the LF traces produced by the Magnograph, the Rotescograph, and the LMA-250. We leave it to the readers' individual judgement as to which one they may prefer. It may, however, be in order for us to add illustrations of some basic situations, as provided by the respective instrument-designers themselves.

Figure 30a is a reproduction of a Rotescograph LF trace (9), showing the effect of broken wires of different diameters and gaps, namely:

anomaly #1 shows a small (0.03 in. diam × 4 in. long) broken wire;

anomaly #2 shows a 0.062 in. diam × 3 in. long broken wire;

anomaly #3 shows a 0.030 in. diam × 26 in. long broken wire;

anomaly #4 shows a 0.060 in. diam × 6 in. long broken wire;

anomaly #5 shows a 0.042 in. diam × 0.79 in. long broken wire.

Figure 30b illustrates (9) the shape of the Rotescograph's LF trace as a gap-length is steadily increased (minimum in case A, maximum in case C). In both charts the sequence of events is from left to right. With the rope moving through the sensor-head as before, but with anomalies that cause positive, rather than negative, perturbations, the LF trace will be a mirror image of the ones shown. Figure 30c illustrates (10) both the LMA and LF chart-traces of the Rotescograph.

Figure 31 is a copy of a Magnograph chart (11). Sequence of events is again from left to right on the chart. It is interesting to note, since our test ropes include both positive and negative perturbations, how the LF trace responds to each type of defect.

The corresponding LMA-250 chart traces (12), obviously obtained on the same rope as the foregoing Magnograph ones, are illustrated in Figure 32.

Finally we include Figure 33. Here we combine the LF traces produced by the LMA-250, the Rotescograph, the Magnograph, and the German WBK instrument. All traces were obtained identically by moving an induction-coil with a variable speed electric motor backwards and forwards along a 4 in. stroke inside a $1\frac{5}{8}$ in. (4.13 cm) diam × 3-ft long plastic tube. The coil had 10 turns. A magnetic field intensity of 255 A/m was produced at the centre of the coil with a test-current of 1.0 A. The resulting magnetic flux density was 3.2 Gauss, and the total flux through the coil 38.6 Mx. The set-up was designed to simulate a wire-rope's leakage flux. A photograph (Fig. 55) of the foregoing procedure in progress with the German WBK instrument, is attached (Appendix 4).

Figure 33 shows (as can also be seen in the other appended LF chart-traces) that the Magnograph and the WBK signals are, basically, similar to each other. The better delineation of the German WBK's LF-trace is due to this instrument's very narrow differential coil for sensing the leakage flux: 5 mm, as opposed to considerably more for the other testers (e.g., some 50 mm for the Magnograph). One trade-off for this 5 mm feature is the fact that this instrument needs an array of sense-coils when testing a range of rope-sizes that can all be handled quite satisfactorily with the standard coil of the other testers. However, should specific needs demand it, such as detection of surface defects, the available option can be beneficial.

Figure 33 also shows that the LMA-250 and Rotescograph signals are similar to each other. However, the Magnograph and WBK instruments' LF sensors are designed to respond to the radial component of the leakage-flux, while the LMA-250 and Rotescograph sense the axial component of the leakage flux.

With the benefit of hindsight we can now say that the 4 in. stroke was not long enough to do equal justice to all instruments tested. It should have been considerably longer, say about 16 in.

Using an electronic back-up device

Several duplicate charts are included among Figures 1 to 20. One reason for doing this is to illustrate the advantages to be obtained by a judicious use of electronic back-up records.

In our present test series the Rotescograph was not equipped with a taping device. However, we had tapes of all Magnograph tests, and of the March, 1990, LMA-250 tests. This enabled us to better assess several important chart sections that were, otherwise, not clear enough. The improvements were obtained by chosing other gain and/or speed settings for the LMA and/or LF charts, than had been submitted to us originally.

Figures 7a and 8a may be noted in this respect. These were submitted to us by FAX, to replace earlier, and even poorer, charts. Figures $7b_1$ and $8b_1$ show what can be achieved by using back-up tapes.

Generally speaking we suggest: (a) that paper charts be, preferably, recorded at LMA sensitivities of 1.0% per major chart division, and at speeds of no less than 5 mm/sec, and (b) that electronic back-up records be routinely obtained. Figures 1b, 1c, and 2b, as well as 9a and 10a, illustrate how difficult it is to obtain useful information from charts run at excessively slow speeds.

In addition to the aforementioned reasons, it is also very useful to have electronic back-up records in cases where the full LMA and/or LF signal amplitudes were not accomodated by the recorder pens. Even in these cases the electronic device will contain the full signal amplitudes, unless it be saturated due to injudicious gain-settings. Appropriate charts can, therefore, be prepared without the need of time consuming and expensive repeats of the test-runs themselves.

Calibration

As mentioned in previous CANMET reports (e.g., in ref 3), and elsewhere (e.g., in ref 13) it is recommended practice to tape a calibration-wire to the rope being tested, at a known distance from a permanent fixture, such as a cage, skip, or counterweight. By doing so the operator: (a) renders the distance measurements on his charts more meaningful, (b) facilitates the correct splicing together of charts that were obtained with two, rather than a single, instrument set-up, and (c) facilitates the proper evaluation of his LMA-gain chart settings. To quote for the Rotescograph (13):

It is good practice to use a calibration wire to properly evaluate the "D.C. SENS" settings.

a) a calibration wire should be three to six in. long, and have a diameter approximately equal to the diameter of the wires in the rope under test;

b) this wire segment is to be taped securely to the rope in a direction parallel to its axis, and usually between two strands. It may be located anywhere along the length of the rope, but it is most practical to locate it within 100 ft of the strand or the end of a test, e.g., 100 ft above the conveyance. It should be inserted before the test head is clamped on the rope, if possible;

c) when the test has commenced the inlaid wire will pass through the test head and cause an anomaly on both channels,

— *the D.C. channel should display the characteristic 'dipole' pattern. This pattern will be opposite in polarity to that emitted when a broken wire is detected, as long as the rope is travelling in the same direction;*

— *the A.C. channel should indicate an increase in area in the form of a spike. The amplitude of the spike, or "area increase", will depend on the diameter of the wire relative to the total steel area of the rope. Because of the scanning length of the test head, the amplitude of the anomaly will be smaller than its true value. It would approach its true value if the length of the segment was 8-10 in.*

We illustrate such a calibration procedure for the Magnograph in Figure 10b. We note the following: (a) in the section marked "three calibration wires added", we taped three 0.080 in. diam × 3-ft long wires into three adjacent valleys of test-rope 'B', with their ends as parallel to each other as possible. The two conspicuous spikes on the LF trace clearly indicate the presence of these added wires, while the corresponding +1.0% rise on the LMA trace corresponds remarkably well to the +1.08% theoretical LMA value (note: total test-rope metallic area is 1.399 in^2; metallic area of the three 0.080 in. diam wires is 0.015 in^2), (b) in the rope length following these three wires, 6-ft closer to the rope-end, we taped two more of these 0.080 in. diam × 3-ft long wires to the rope, this time into a single valley of the strands. We left a 5 mm gap between the wire ends. Consequently, three spikes should appear on the LF trace (marking beginning and end of these wires, plus the 5 mm gap), and a +0.4% rise on the LMA trace. The three spikes are clearly seen. The LMA perturbation is too small to evaluate meaningfully with the LMA-gain setting used.

For the LMA-250 our aforementioned calibration procedure is recorded in Figure 6. The presence of both calibration groups — one with the 3-ft long wires in three adjacent strand valleys, and one with the two 3-ft wires and a 5 mm gap in a single valley — is again clearly in evidence on both the LF and LMA chart-traces. The first group caused a +1.0% rise on the LMA trace, and the second a +0.5% rise. Both match the theoretical values remarkably well. We propose to comment on the possibility of how best to utilize the available (but unused at present) LF channel calibration information in a future CANMET report.

Step-response and quantitative resolution

In our test-ropes 'A' and 'B' the length of almost all artificial defects is in the order of 6 ft, i.e., much longer than the sensor heads used. This test-series does not,

therefore, address the problem of the different instruments' quantitative resolution, i.e., that of the instruments' averaging or scanning lengths. We might discuss this question in future, on the basis of further experiments. However, in response to suggestions that even at this time we briefly address this problem, we do so: (a) by recording the different sensor-head lengths in our comments on Fig. 35, and (b) by noting relevant results obtained by others (11, 12, 14).

In Figures 31 and 32 we reproduce (from references 11 and 12) an interesting comparison of the LMA-series and Magnograph instruments, as obtained on the self-same, 19 mm diam stranded wire-rope, with well-defined, standard, flaws. Moreover, we elaborate this performance-comparison by juxtaposing (Fig. 32a) these strip-charts, produced at similar sensitivity and chart-speed settings. Differences are in evidence; however, they are (Table 10, Appendix 3) within the previously noted ±2.0% benchmark range that we consider "acceptable". We do not know the value of the corresponding "true" LMA chart-readings.

We also compare the step-response of the two instruments at the start of the three missing-wire rope section (Fig. 32b). The parameters in this figure reflect the method of describing, in electrical engineering terms, the step-response as being the LMA-trace section between 10% and 90% of the total response. As shown, this corresponds to an 8.6 in. measured length for the Magnograph, vs a 4.5 in. measured length for the LMA-series instrument. The 8.6 in. length can be noted in context with Fig. 32c (from ref. 14). Here it is shown that the Magnograph — with a 9 in. inside span of its metallic-area pole elements — measures a metallic area loss with 90% efficiency in case of a 9 in. defect-length, and with 100% efficiency if the rope-defect is some 11-13 in. long.

Test-rope construction — some problems

With the benefit of hindsight, we can now say that while we were correct in placing our artificial rope-defects on a standard spacing, we should have chosen considerably greater gaps between the anomalies than the six ft actually used. Moreover, it would have been better not to let two types of defects overlap each other, such as the three-ft of magnetite filled core (B13) and the six-ft of 7.7% LMA (B12 + B13). Actually the chart traces for test-rope 'B' are easier to interpret than those obtained for test-rope 'A'.

The unforeseen wire-breaks that occurred during manufacture, as the rope was being closed, were referred to earlier in this report. Also, it appears we did not succeed

in maintaining uniform cross-sections at the start and finish of the major LMA defect-sections. In other words where three outer, and 12 inner, wires were replaced by smaller ones, some of these welded wire-ends did not line up properly (better so in some, and worse in other cases). We suggest that this is one of the reasons why we find negative LMA values in between the major LMA sections where, theoretically, no LMA should be present. Other reasons for this unforeseen anomaly include: (a) unplanned wire-breaks in these sections, (b) slightly longer than planned lay-lengths, due to deformation of the test-ropes during manufacture, and (c) the probability that extended, and overlapping, magnetic fields existed beyond the sensors, which affect the instrument's quantitative resolution, i.e., that a phenomenon was present where two adjacent anomalies create additive results.

As for the reasons of having, on occasion, even positive LMA values in-between the major LMA defect sections: we can only suggest that this is caused by imperfect setting of the 0.0% LMA-loss reference line.

Magnetic interference

All EM instruments are surrounded by a magnetic leakage field. The smaller this field, the better, because this will minimize the influence of foreign ferrous objects upon the instrument's output signals. Our contractor undertook tests to determine the effect of such magnetic interference, as caused by a stationary steel object close to the instrument's sensor head.

The procedure consisted of placing a $1\frac{3}{8}$ in. rod inside the test head, and zeroing the instrument to this reference. Then a $1\frac{1}{2}$ in. rod was placed parallel to the sensor-head in various positions, as shown in Figure 34a. The test results are shown in Figure 34b. As may be seen, the Rotescograph was the most, and the LMA-250 the least affected by this size of stationary object. Also, at a distance of 18 in., there was no effect on any of the instruments.

In retrospect: the results would have been more meaningful, had: (1) a typical test set-up been replicated by having the sensor-head installed around a long wire-rope instead of the relatively short $1\frac{3}{8}$ in. rod, and (2) had the foreign ferrous object been non-stationary.

Magnetic saturation of rope

Although our test-results provide, by themselves, a fair indication of the satisfactory magnetic rope-saturation achieved with all the instruments used, an experiment

was conducted by our contractor to actually measure the intensity of the magnetic field inside the different sensor-heads. This was done with a 1.927 in. diam (4.89 cm diam, i.e., A = 18.78 cm^2) brass tube, which fitted snugly inside the various sensor-heads. It contained two 14 in. long solid mild-steel cylinders with a 0.040 in. thick aluminum spacer between them. This spacer contained a 0.437 in. wide × 0.250 in. long channel, to accomodate an Ohio Semitronics HR-36 Hall-device. The latter was calibrated to give a magnetic flux density reading 'B' (in Gauss) of 10 mV/K Gauss (where Gauss = Mx/cm^2) at a 92.42 mA excitation current. The total flux through the centre of the apparatus was, therefore, B×A = B×18.78 Mx.

Test results are illustrated in Figure 35 for distances up to 5 in. from the centre of the sensor-heads. These heads are about 14-16 in. long for the Rotescograph and Magnograph, and in the order of 8-11 in. for the WBK and LMA-250 testers. As shown in Figure 35, all instruments have the same basic flux density distribution pattern, except for the Magnograph.

The more uniform this pattern along the sensor head, the lower the magnitude of the magnetic field-induced Eddy currents which: (a) counteract the field, and (b) degrade the instrument's signal to noise ratio. Also: the areas under the distribution-curves are a measure of the magnetic field strength in the magnetized rope sections. Hence, the larger these areas, and the smoother the patterns, the better.

Operating convenience

In our list of "desirable instrument characteristics" we referred to a number of physical instrument features prospective users might wish to bear in mind. These include operating convenience, as represented, for instance, by the dimensions and weights of the major system components (such as the sensor-heads, the electronic control sections, and the recorder-sections). The lighter and more compact the system components, the better — all other important instrument features being equal. These data are readily available from the manufacturers' sales literature. We suggest that in this, as in all other respects, final decisions must rest with the instrument users. We merely hope to be of assistance with the comparative information provided. We might add, however, that all the North-American instruments used in our project were standard commercial models, in general use for a number of years. The German tester represented a prototype model of their latest design.

SUMMARY

As part of our Canada/NB MDA project we undertook extensive in-house work to study the results of a series of prior destructive and non-destructive wire-rope examinations (1, 2, 3). A list of the summary conclusions was published (3). In addition to our in-house endeavours, we also undertook a major contracted project. This report includes some of the results obtained by the latter work.

Among other results we conclude that human factors — in particular questions of competency and of certification — are among the top problems of non-destructive wire-rope testing with EM instruments. In particular the problem of proper instrument calibration, and awareness of the physical limitations of the respective test instruments need to be noted in this respect. Other problems the operators must watch for relate to effects caused by surrounding ferro-magnetic objects (in particular moving ones), and by electrical interference. They also need to be aware of the importance of checking for repeatability, correct setting of the 100% reference levels on the LMA chart traces, correct splicing of charts in case of multiple instrument set-ups, and the difficulty of preparing LBS estimates on the basis of actually obtained LMA and LF chart records.

In this report we present specific examples arising from some of the aforementioned problems. We also demonstrate, by means of an extensive list of tabulated data and chart-traces, the repeatability aspect of the EM test results. We shall publish additional results of our contracted work in forthcoming CANMET reports.

ACKNOWLEDGEMENT

The reel-to-reel test series described in this report was undertaken on the shop-floor of Wire Rope Industries Ltd. at Pointe Claire, Quebec. Their wholehearted support of the project in general — and of the test-rope design, fabrication, and testing phases in particular — is gratefully acknowledged, with special thanks to Messrs. Delorme, Savory and Bole.

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APPENDIX 1

Chemical composition of trapped debris —

E-96 magnetite, MP-20 and MP-41 iron-filings

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DATA SHEET

MAGNETITE

Fe_3O_4

E96 - E98 - E99 - E100

Typical Chemical Analysis

Fe	68.0%
P	0.06%
S	0.03%
SiO_2	1.85%
Al_2O_3	0.33%
TiO_2	0.13%
Cu	0.03%
K_2O & Na_2O	0.12%
Others	0. 15%

Physical Description

Color		Black
Fineness	Grade E96	96% thru 325 mesh
	Grade E98	98% thru 325 mesh
	Grade E99	99% thru 325 mesh
	Grade E100	100% thru 325 mesh
Specific Gravity		5.0
Magnetics		96%
Package		50 lb. bags
		Super Sacks
		Bulk

The information and data contained herein are believed to be correct. However, we do not warrant either expressly or by implication, the accuracy thereof. We recommend that the prospective user determine the suitability of our materials and suggestions before adopting them on a commercial scale. No statement in this bulletin is to be construed as violating any copyright or patent.

CUSTOMER	CUSTOMER ORDER NO.	
WIRE RODE INDUSTRIES	ECHANT.	88-963

DELIVERY NOTE NO.

MP 11380-1

SHIPPING DATE: 12/20/88

QUANTITY: 5 LBS.

PACKAGING: 5 LB. PINTE

LOT NO. 4396

PRODUCT CODE:

MP 20	100.00	%
LUBRICANT		%
GRAPHITE		%
COPPER		%
NICKEL		%
		%

PHYSICAL

SCREEN ANALYSIS
% BY WEIGHT U.S. STANDARD SIEVE

+ NO. 4		%
+ NO. 8		%
+ NO. 14		%
+ NO. 20	-	%
+ NO. 30		%
+ NO. 40		%
+ NO. 50	3.7	%
+ NO. 60		%
+ NO. 80	39.4	%
+ NO. 100	25.4	%
+ NO. 140		%
+ NO. 200	27.8	%
+ NO 325		%
PAN	3.7	%

APPARENT DENSITY (gm/cc)
3.66

FLOW (SECONDS)

HALL

OTHER

CHEMICAL

CHEMICAL ANALYSIS
% BY WEIGHT

CARBON	0.110	%
OXYGEN	0.420	%
SULPHUR	0.025	%
PHOSPHORUS	0.020	%
MANGANESE	0.320	%
SILICON	0.100	%
ACID INSOL		%
MOLYBDENUM		%
NICKEL		%
TOTAL IRON		%
VANADIUM		%
TOTAL CARBON IN PREMIX		%

BRIQUETTING

TYPE OF TEST SPECIMEN:

GREEN PROPERTIES

COMPACTING PRESSURE T.S.I.	GREEN DENSITY gm/cc	GREEN STRENGTH P.S.I.

SINTERING

ATMOSPHERE: ENDO at 30°F DEW POINT

TIME: MINUTES at 2050°F TEMP.

SINTERED PROPERTIES

STANDARD	T.R.S. OR "K" FACTOR P.S.I.	HARDNESS	DIMENSIONAL CHANGE +/- (FROM DIE SIZE)

COMPOSITION OF POWDER MIX FOR TESTS:

1-(White) Customer's Copy; 2-(Pink) Head Office Copy;
3-(Green) Plant Copy; 4-(Yellow) Plant Manager's Copy

APPROVED BY,

WIRE RODE INDUSTRIES | ECHANT. | 88-963

DELIVERY NOTE NO.

MP 11383-2

SHIPPING DATE: 12/20/88

QUANTITY: 5 LBS.

PACKAGING: 5 LB. PINTE

LOT NO. 3539

PRODUCT CODE: .

MP 41	100.00	%
LUBRICANT		%
GRAPHITE		%
COPPER		%
NICKEL		%
		%

PHYSICAL

SCREEN ANALYSIS
% BY WEIGHT U.S STANDARD SIEVE

+ NO. 4		%
+ NO. 8		%
+ NO. 14		%
+ NO. 20		%
+ NO. 30		%
+ NO. 40		%
+ NO. 50		%
+ NO. 60		%
+ NO. 80		%
+ NO. 100		%
+ NO. 140	11.8	%
+ NO 200	30.9	%
+ NO 325	28.9	%
PAN	28.4	%

APPARENT DENSITY (g/cm³)
2.59

FLOW (SECONDS)

HALL

OTHER

CHEMICAL

CHEMICAL ANALYSIS
% BY WEIGHT

CARBON	0.072	%
OXYGEN	0.830	%
SULPHUR	0.016	%
PHOSPHORUS	0.020	%
MANGANESE	0.300	%
SILICON	0.110	%
ACID INSOL		%
MOLYBDENUM		%
NICKEL		%
TOTAL IRON		%
VANADIUM		%
TOTAL CARBON IN PREMIX		%

BRIQUETTING

TYPE OF TEST SPECIMEN:

GREEN PROPERTIES

COMPACTING PRESSURE T.S.I.	GREEN DENSITY g/cm³	GREEN STRENGTH P.S.I.

COMPOSITION OF POWDER MIX FOR TESTS:

SINTERING

ATMOSPHERE: ENDO at 30°F DEW POINT

TIME: MINUTES at 2050°F TEMP.

SINTERED PROPERTIES

STANDARD	T.R.S. OR "K" FACTOR P.S.I.	HARDNESS	DIMENSIONAL CHANGE "/" (FROM DIE SIZE)

1-(White) Customer's Copy; 2-(Pink) Head Office Copy;
3-(Green) Plant Copy; 4-(Yellow) Plant Manager's Copy

APPROVED BY:

APPENDIX 2

Detailed analysis of a few chart-traces

Test Rope A

The LMA 250 instrument

In case of the April 5, 1989, tests with the LMA 250 instrument (Figures 3 and 17) we noted the following:

(a) the location of the 100% reference level was correctly placed as a straight horizontal line along the approximately 169 ft long A17 rope section. There are no anomalies in this section. The LMA trace remains at the 0% LMA level. Once the anomalies are reached, however, these cause the LMA output to deviate from the 0% loss level. This in turn activates the zero seeking integrator device; it seeks zero at a certain rate, an effect often referred to as "droop". In the present case of a short rope its effect (Tables 4 and 8) is minor, and can be neglected;

(b) the start and end of the broken- and missing wire section A2 was clearly delineated on the LF trace, together with an associated 2.0% LMA (max), over a distance of some 4 ft. The LMA trace reverted to the 100% reference level, in rope-section A2 – A3;

(c) the 6 ft stretch A3 of true 7.0% LMA (due to a change in outer-wire diameters) with broken outer-wire(s) at A4, was recorded as a 7.6% LMA (max) over a 7 ft rope stretch. The LMA trace remains some 2.5% below the 100% reference level in rope section A3 – A6;

(d) the 6 ft stretch A6 of true 7.6% LMA (due to a change in outer-wire diameters) with broken outer-wires (about one at A5, and four at A7) as well as inner-wires (about two at A7) at the extremities, was recorded as an 8.0% LMA (max) over some $9\frac{3}{8}$ ft of rope, with clear LF signals at the extremities, plus several additional unmapped LF perturbations along this rope section. The LMA chart trace not only returns to the 100% reference level in rope section A6 – A9: it rises 0.6% above it;

(e) the 6 ft stretch A9 of true 7.2% LMA (due to a change in inner-wire diameters), with: (a) broken outer- (about one) and inner- (about three) wires at A8, plus (b) a 3 ft long stretch (A10) where the rope's fibre core had been replaced with a magnetite-powder filled plastic tube, was recorded as a 4.5% LMA (max) over about 6 ft of rope. Within this rope stretch the beginning of the magnetite-filled rope core is conspicuously recorded on both the LMA (as a sudden 1.6% LMA change) trace and the LF signal. The 1.6% LMA change is, however, gradually

dissipated along a 3 ft rope stretch, until once again a total LMA of 4.8% is attained. In rope-section A9 – A11 the LMA again rises above the 100% reference level, by about 0.7% ;

(f) the 6 ft stretch A11 contains an iron-filings filled plastic tube in the rope core, with at least one broken inner-wire at A12. Moreover, the iron-filings filled core is overlapped along A13 by a true 7.7% LMA (due to a change in inner-wire diameters). This true 7.7% LMA stretch then extends along section A14, with broken inner-wires (possibly only one) at A15. The beginning and end of the 7 ft iron-filings filled rope core section A11 is clearly recorded on the LF trace. An abrupt 1.5% dip in the LMA trace at the extremity of the A13 section indicates the interface of the A13 — A14 sections. As noted before, the A13 section is said to overlap along 3-4 ft, the iron-filings filled core A11. The true 7.7% LMA was recorded at 7.5% (max);

(g) in the rope sections between the four major LMA stretches the LMA signal-trace behaves as follows: (1) section A2 to A3: 0.0%, (2) section A3 to A6: -2.5%, (3) section A6 to A9: +0.6%, (4) section A9 to A11: +0.7%.

Test Rope B

The LMA 250 instrument

In case of the April 5, 1989, tests with the LMA 250 instrument (Figures 4a and 13) we noted the following:

(a) the gradual change, or "hump", in the LMA trace at the initial rope-end was misinterpreted by the instrument operator. It shows up on the LMA 250 (Fig. 4a), the Magnograph (Fig. 8a), and also on the Rotescograph (Fig. 2a) instrument charts. There is no definite LF signal associated with it. No defects were built into the rope here. Most likely, it indicates the beginning of the test-rope proper. Had a marker been affixed to the rope where measurements were to be counted from, as advocated in CANMET report #89-40, this uncertainty would not have arisen. Whether of spurious or genuine origin, this "hump" — it measures +3.0% on the LMA-250 (Fig. 4a); +2.5% on the Magnograph (Fig. 8a), and +1.2% on the Rotescograph (Fig. 2a) — misled the LMA 250 instrument operator (an engineer with exceptionally wide practical and theoretical background in operating various EM testers) in setting the 100% chart-reference level 3.0% below the true level, along the B17 rope section. As in case of test-rope A, the trace remains at the 0% LMA level along the entire rope section (B17) without defects. Then it droops a negligible 0.5% as it passes from one end of the defective rope section to the other. In this report we corrected the %LMA values that were reported to us for the abovenoted 3.0% error. The incident underlines one of the current problems: the difficulty due to an incorrect setting the 100% reference level. The advantage , therefore, in obtaining absolute, rather than relative, LMA values follows logically. The relevant process will be discussed in a future CANMET report;

(b) the broken- and missing-wires in section B2 are conspicuous on the LF trace, in conjunction with an associated LMA of 3.3% (max), over a distance of some 3 ft. The LMA trace remains some 0.5% below the 100% reference level in rope section B2 – B3;

(c) the 6 ft stretch B3 of true 7.0% LMA (due to a change in outer wire diameters), with broken wire(s) at B4, was recorded as a 9.0% LMA (max) over about an 8 ft rope length, with clear LF signals at each end of this rope stretch. The LMA trace remains some 1.0% below the 100% reference level in rope sectionB3 – B6;

(d) the 6 ft stretch B6 of true 7.6% LMA (due to a change in outer-wire diameters) with about three broken outer-wires at B5, and broken inner- (about two) and outer-wires (about five) at B7, was recorded as a 9.5% LMA (max) over some 10 ft of rope length; within this stretch a 0.8% LMA peak is conspicuous (Fig. 13). The location of both the three (B5) and seven (B7) broken wires is recorded on the LF channel, although one cannot determine their number, or the ratio of the broken inner- to broken outer-wires. The rather gradual change of the LMA trace along the B5 – B6 stretch is noticeable (up to the 0.8% peak), when compared to the rate of the LMA trace changes at the other three (7.0%, 7.2%, and 7.7%) LMA locations;

(e) the 6 ft stretch B9 of true 7.2% LMA (due to a change in inner-wire diameters) with broken inner-wires (about two) at B8, and more broken inner-wires (about four) at B10 — with several more (B11) at unknown locations — was recorded as a 9.2% LMA (max) over about 6 ft of rope length, with conspicuous LF signals at each extremity of this rope section. No broken wires are in evidence along the B9 – B12 rope length of some 6 ft (Fig. 13);

(f) the 6 ft B12 + B13 of true 7.7% LMA (due to a change of inner-wire diameters) includes a 3 ft section (B13) where the rope's fibre-core has been replaced by a magnetite-powder filled plastic tube. Moreover, there are broken wires (about four) at B14. These defects were recorded (over about 7 ft) as an 8.0% LMA (max), with a noticeable sudden change along about 4 ft of rope to 7.0-7.5% LMA at the B12 to B13 interface, i.e., at the point where the magnetite powder filled plastic tube is said to stretch to. A conspicuous perturbation of the LF trace at this juncture is also in evidence. The change from this 7.0% - 7.5% LMA level to the 100% reference level (along some 6 ft of rope length) is noticeably slower than is the change from the 100% level to the 8.1% LMA value along the B12 rope stretch;

(g) the approximately 7 ft rope stretch B15 along which the rope's fibre core is said to be replaced by an iron-filing filled plastic tube is clearly delineated, both on the LMA and the LF traces. The LMA signal rises by a maximum of 2.0% above the 100% reference level, although the inside cross-section of this plastic tube actually equals about 21.9% of the wire-rope's total metallic cross-sectional area, and the fill-factor is some 55%;

(h) according to the rope manufacturer's records the iron-filings filled core at B15 is separated by a 6 ft rope stretch without defects from another 6 ft of core section (B16) which contains a plastic tube filled with corrosion products. There is no

clear evidence on either the LMA or the LF instrument-traces of the presence of these corrosion products, even though a considerable percentage of the wire-rope's cross-section is taken up by them;

(i) in the rope-stretches between the five major LMA sections the LMA signal-trace behaves as follows: (1) section B2 to B3: –0.5%, (2) section B3 to B6: –1.0%, (3) section B6 to B9: –1.0%, (4) section B9 to B12: 0.0%, (5) section B13 to B15: 0.0%.

The Rotescograph instrument

With this instrument measurements were taken on April 5 (Fig. 2a), April 10 (Fig. 2c), and April 15 (Fig. 2b), 1989, at the respective chart speeds of: 5 mm/sec (this chart can be directly compared with that of the LMA 250 instrument); 0.5 mm/sec; and 1 mm/sec. On the basis of the 5 mm/sec chart we noted the following:

(a) this instrument's operator was not misled by the "hump" in the LMA trace. He placed the 100% reference along the level of the B1 rope section (Fig. 2a). However, he ignored the approximately $1\frac{1}{2}$% shift of the LMA trace that occurred from one end to the other end of the "defective" rope section. This resulted in misconceptions, such as: (1) the assumption of a 1.4% LMA along rope section B17 (in fact this rope section does not contain any defects), and (2) missing the sections where metal was added in the rope-core, rather than removed from the rope's cross-section;

(b) the start and end of the broken- and missing-wires in section B2 are conspicuous both on the LF and the LMA traces. The LMA trace records an associated LMA of some 2.5% (vs 3.3% on the LMA 250 chart), i.e., an LMA corresponding to at least three broken outside wires. Both the Rotescograph's and the LMA 250's LMA trace remain some 0.4% to 0.5% below the 100% reference mark in rope section B2 – B3;

(c) the 6 ft stretch B3 of true 7.0% LMA (due to a change in the outer wire diameters), with broken outer-wires (about two) at B4, was recorded as a 6.2% LMA (max), over an approximately 7 ft rope length, with clear LF signals at both ends of this stretch. The LMA trace of the Rotescograph remains 0.4% below the 100% reference level in rope section B3 – B6;

(d) the 6 ft stretch B6 of true 7.6% LMA (due to a change in outer-wire diameters) with broken outer wires (about three) at B5, and another set of broken wires

(about five outer- plus two inner-wires) at B7, was recorded as a 6.1% LMA (max) over some 10 ft of rope length; in this section an approximately 0.5% LMA peak is conspicuous (Fig. 11). The location of both the three (B5) and seven (B7) broken wires is recorded on the LF channel, although one cannot determine their number, or the ratio of the broken inner- to broken outer-wires. The rather gradual change of the LMA trace along the B5 – B6 stretch (up to the 0.5% peak) is just as noticeable here, as it is in case of the LMA 250 instrument trace;

(e) the 6 ft stretch B9 of true 7.2% LMA (due to a change of inner-wire diameters) with broken inner-wires (about two at B8, and four at B10) — with several more (B11) at unknown locations — was recorded as a 5.7% LMA (max) over about 6 ft of rope, with conspicuous LF signals at each extremity of this rope section. No broken wires are in evidence along the B9 – B12 rope length of some 6 ft (Fig. 11);

(f) the 6 ft stretch B12 + B13 of true 7.7% LMA (due to a change in inner-wire diameters) included a 3 ft section (B13) where the rope's fibre core has been replaced by a magnetite-powder filled plastic tube. Moreover, there are broken inner-wires (about four) at B14. These defects were recorded, over about a 9 ft stretch, as a 5.2% LMA (max), with a noticeable sudden change, along about 5 ft of rope, to 4.5% LMA at the B12 to B13 interface, i.e., at the point where the magnetite-powder filled plastic tube is said to stretch to. A conspicuous perturbation of the LF trace is also in evidence at this point. The LMA trace remains about 0.8% below the 100% reference level along the rope section B13 – B15 (while the LMA 250 and Magnograph signals are along the 100% reference level here). Also, the change of the LMA trace from the 4.5% towards the 100% reference level is noticeably slower than is the change from the 100% level to the 5.2% LMA along the B12 rope stretch;

(g) the approximately 7 ft rope stretch B15, along which the rope's fibre core is said to be replaced by an iron-filings filled plastic tube, is clearly delineated both on the LMA and LF traces. The LMA signal rises by a maximum of 1.6% above the 100% reference level, although the inside cross-section of this plastic tube equals about 21.9% of the wire-rope's total metallic cross-sectional area, and the fill-factor of the filings is some 55%;

(h) according to the manufacturer's records, the iron-filings filled core at B15 is separated by a 6 ft rope-stretch without defects from another 6 ft of core section (B16) which contains a plastic tube filled with corrosion products. There is little, if any, evidence on either the LMA or the LF instrument-traces, of the presence of

these corrosion products, even though a considerable percentage of the wire-rope's cross-section is taken up by them;

(i) in the rope-stretches between the five major LMA sections the LMA signal-trace behaves as follows: (1) section B2 to B3: –0.4%, (2) section B3 to B6: –0.4%, (3) section B6 to B9: 0.0%, (4) section B9 to B12: +0.5%, (5) section B13 to B15: –0.8%.

In case of the April 15, 1989, Rotescograph test with a 1 mm/sec chart-speed, we noted the following (Fig. 2b):

(a) during this test, the rope passed through the Rotescograph in reverse order to the direction used for the previously described April 5, 1989, test;

(b) again the LMA trace "drooped" by some 1.0% from one end to the other end of the "defective" rope section. However, it is now more difficult to definitely establish the 100% reference level on the chart than it is in case of the April 5 test with a 5 mm/sec chart speed. Moreover, with the 1 mm/sec chart speed the LF signals are too crowded, adding to the difficulty of proper chart interpretation;

(c) at B2 the LMA now is 1.8% (vs the 2.5% and 3.3% noted previously for the Rotescograph and LMA-250). The LMA trace once again remains some 0.4% below the 100% reference level in rope section B2 – B3;

(d) at the four major artificial LMA anomalies (B3, B6, B9, and B12 + B13) the LMA values are only about 4.0%-5.0%, rather than the true 7.0%-8.0% order of magnitude;

(e) the abrupt 0.5% LMA change at the B12 – B13 interface, i.e., where the magnetite powder filled plastic tube is said to stretch to in the rope core, is again clearly in evidence;

(f) in the rope-stretches between the five major LMA sections the LMA signal-trace behaves as follows: (1) section B2 to B3: –0.4%, (2) section B3 to B6: –0.3%, (3) section B6 to B9: 0.0%, (4) section B9 to B12: +0.4%, (5) section B13 to B15: +0.4%;

(g) the overall shape of the LMA chart-trace retains all the characteristic features observed on the 5 mm/sec chart. However, quantitatively, the results differ along the major LMA sections (Table 5).

The instrument's chart speed was set at 0.5 mm/sec during the April 10, 1989, test (Fig. 2c). At this setting the results become of little, if any, use. Even so, the "droop" of the LMA trace is again noticeable, although much less than in the two previous cases (Figures 2a and 2b). We also noted:

(a) at the four major artificial LMA anomalies the maximum %LMA values are as follows: (1) along B3: –5.0%; (2) along B6: –5.0%; (3) along B9: –5.0%; (4) along (B12 + B13): –4.6%;

(b) in the rope-stretches between the five major LMA sections the LMA signal-trace behaves as follows: (1) section B2 to B3: –0.5%, (2) section B3 to B6: –0.6%, (3) section B6 to B9: –0.6%, (4) section B9 to B12: –0.2%, (5) section B13 to B15: –0.7%.

The Magnograph instrument

In case of the April 4, 1989, tests with the Magnograph (Figures 8a, $8b_1$, and 12) we noted the following:

(a) the location of the distance-recording line on the chart shifts vertically as the instrument is being moved backwards along a once already traversed rope section;

(b) the instrument operator was not misled by the presence of the "hump" on the LMA trace, when setting his 100% reference level. He set it, correctly, along the level of the B1 = B17 rope sections;

(c) the 100% reference level did not shift from one end to the other end of the "defective" rope section;

(d) the start and end of the broken- and missing-wires at section B2 are conspicuously recorded on both the LF and LMA chart traces. The associated LMA is 2.8 – 3.0%. As with the other instruments, the LMA trace remains some 0.5% below the 100% reference level in rope section B2 – B3;

(e) the 6 ft stretch B3 of true 7.0% LMA (due to a change in the outer-wire diameters), with broken outer-wire(s) (about two) at B4, was recorded as a 7.2% LMA (max), over an approximately 7 ft rope length, with clear LF signals at both ends of this stretch. The LMA trace of the Magnograph remains 0.7% below the 100% reference level in rope section B3 – B6;

(f) the 6 ft stretch B6 of true 7.6% LMA (due to a change in outer-wire diameters) with broken outer-wires (about three) at B5, and another set of broken wires

(about five outer- plus two inner-wires) at B7, was recorded as a 7.6% LMA (max) over some 8.6 ft of rope length. In this section an approximately 0.5% LMA peak is present (Fig. 12), but is, perhaps, less obvious than in the LMA-250 and the Rotescograph LMA traces;

(g) the 6 ft stretch B9 of true 7.2% LMA (due to a change of inner-wire diameters) with broken inner-wires (about two at B8, and four at B10) — and several more (B11) at unknown locations — was recorded as a 7.8% LMA (max) over about 8.6 ft of rope, with conspicuous LF signals at each extremity of this rope section. No broken wires are in evidence (Fig. 12) along the B9 – B12 length of some 4 ft. The LMA trace regains the 100% reference level in the B9 – B12 section;

(h) the 6 ft stretch B12 + B13 of true 7.7% LMA (due to a change in inner-wire diameters) included a 3 ft section (B13), where the rope's fibre core has been replaced by a magnetite-powder filled plastic tube. Moreover, there are broken inner-wires (about four) at B14. These defects were recorded, over about a 7 ft stretch, as a 7.3% LMA (max). There is a noticeable perturbation on both the LMA and the LF traces, at the B12 – B13 interface (Fig. 12), i.e., at the point where the magnetite-powder filled plastic tube is said to stretch to. The LMA trace reverts to the 100% reference level in rope section B13 – B15;

(i) the approximately 7 ft rope stretch B15, along which the rope's fibre core is said to be replaced by an iron-filings filled plastic tube is clearly delineated on both the LF and LMA traces. On the LMA trace the extremities of this anomaly are less abrupt than what they are on the equivalent LMA 250 and Rotescograph chart traces. A maximum LMA change of some 1.2% can, however, be observed, even though the inside cross-section of this plastic tube equals about 21.9% of the wire-rope's total metallic cross-sectional area, and the fill-factor of the filings is some 55%;

(j) according to the manufacturer's records the iron-filings filled core at B15 is separated by a 6 ft rope stretch without defects from another 6 ft of core section (B16), which contains a plastic tube filled with corrosion products. There is little, if any, evidence on either the LMA or the LF instrument-traces, of the presence of these corrosion products, even though a considerable percentage of the wire-rope's cross-section is taken up by them;

(k) in the rope-stretches between the five major LMA sections the LMA signal-trace behaves as follows: (1) section B2 to B3: –0.7%, (2) section B3 to B6: –0.7%, (3) section B6 to B9: –0.6%, (4) section B9 to B12: 0.0%, (5) section B13 to B15: 0.0%.

APPENDIX 3

Test results —
Tables 1 to 10, and Figures 1 to 35

Table 1

Test rope A — Max. %LMA in the major LMA rope sections

Rope section symbol	A2	A3	A6	A9	(A13+A14)
True LMA	unknown	-7.0	-7.6	-7.2	-7.7
Rotescograph					
Tests of April 5, 10, and 15, 1989					
5 mm/sec chart speed	-1.4	-4.6 (-2.4)*	-4.8 (-2.8)	-2.9 (-4.3)	-4.1 (-3.6)
1 mm/sec chart speed	-1.6	-5.0 (-2.0)	-5.6 (-2.0)	-2.8 (-4.4)	-5.5 (-2.2)
0.5 mm/sec chart speed	-1.5	-4.5 (-2.5)	-4.9 (-2.7)	-2.8 (-4.4)	-3.8 (-3.9)
LMA-250					
5 mm/sec chart speed					
Tests of 5.4.89	-2.0	-7.6 (+0.6)	-8.0 (+0.4)	-4.5 (-2.7)	-7.5 (-0.2)
Tests of 6.3.90	-2.2	-7.8 (+0.8)	-8.6 (+1.0)	-4.8 (-2.4)	-7.6 (-0.1)
Magnograph					
Tests of 4.4.89					
2.5% LMA/major chart division	-2.0	-6.8 (-0.2)	-7.8 (+0.2)	-5.8 (-1.4)	-7.5 (-0.2)
1.0% LMA/major chart division	-1.8	-6.3 (-0.7)	-7.3 (-0.3)	-5.0 (-2.2)	-6.7 (-1.0)
Tests of 6.3.90					
2.5% LMA/major chart division	-1.9	-6.6 (-0.4)	-7.4 (-0.2)	-5.2 (-2.0)	-6.7 (-1.0)
1.0% LMA/major chart division	-1.4	-6.0 (-1.0)	-6.8 (-0.8)	-4.6 (-2.6)	-6.0 (-1.7)

*: bracketed values = accuracy = true %LMA - NDT %LMA

Table 2

Test rope A — Max. %LMA inbetween the major LMA rope sections

Rope section symbol	A2–A3	A3–A6	A6–A9	A9–A11
True LMA	0.0	0.0	0.0	0.0
Rotescograph				
Tests of April 5, 10, and 15, 1989				
5 mm/sec chart speed	−0.8	−1.4	+0.2	+0.9
1 mm/sec chart speed	−0.6	−0.5	+1.4	+1.8
0.5 mm/sec chart speed	−0.5	−1.2	+0.2	+0.7
LMA-250				
5 mm/sec chart speed				
Tests of 5.4.89	0.0	−2.5	+0.6	+0.7
Tests of 6.3.90	0.0	−2.4	+0.4	+0.8
Magnograph				
Tests of 4.4.89				
2.5% LMA/major chart division	−0.5	−2.0	+0.7	0.0
1.0% LMA/major chart division	−0.2	−1.8	+0.8	+0.5
Tests of 6.3.90				
2.5% LMA/major chart division	−0.8	−1.8	+0.8	+0.2
1.0% LMA/major chart division	−0.2	−1.6	+0.9	+0.6

Table 3

Test rope A — %LMA results at rope core sections with metal fillers

Rope section symbol	A9–A10 at interface	A10		A11		A16
		min	max	min	max	
True LMA	+3.0	+3.0		+11.0		+2.0
Rotescograph						
Tests of April 5, 10, and 15, 1989						
5 mm/sec chart speed	1.0	-1.9	-2.9	-4.1	+0.9	-0.6
1 mm/sec chart speed	1.4	-1.4	-2.8	-5.5	+1.8	-0.6
0.5 mm/sec chart speed	0.9	-1.9	-2.8	-3.8	+0.7	-0.2
LMA-250						
5 mm/sec chart speed						
Tests of 5.4.89	1.6	-3.0	-4.5	-7.5	+0.7	-1.0
Tests of 6.3.90	1.5	-3.2	-4.8	-7.6	+0.8	-1.0
Magnograph						
Tests of 4.4.89						
2.5% LMA/major chart division	1.0	-4.8	-5.8	-7.5	+0.6	-1.0
1.0% LMA/major chart division	0.5	-4.5	-5.0	-6.7	+0.5	-1.0
Tests of 6.3.90						
2.5% LMA/major chart division	0.6	-4.6	-5.2	-6.7	+0.2	-1.0
1.0% LMA/major chart division	0.4	-4.2	-4.6	-6.0	+0.6	-0.6

Table 4 — Test rope A

Shift of 100% LMA ref. level along "defective" rope section

Test details	see Figure No.	Sequence of events A1 ⟺ A17	% shift
Rotescograph			
5 mm/sec chart speed	1a	A1 ⟵ A17	+0.2
1 mm/sec chart speed	1b	A1 ⟶ A17	+1.6
0.5 mm/sec chart speed	1c	A1 ⟶ A17	+0.2
LMA-250			
5 mm/sec chart speed			
Tests of 5.4.89	3	A1 ⟵ A17	+0.5
Tests of 6.3.90	5	A1 ⟶ A17	-0.5
Magnograph			
Tests of 4.4.89			
2.5% LMA/major chart division	7a	A1 ⟵ A17	-0.2
1.0% LMA/major chart division	$7b_1$	A1 ⟶ A17	nil
Tests of 6.3.90			
2.5% LMA/major chart division	9b	A1 ⟶ A17	+0.2
1.0% LMA/major chart division	9a	A1 ⟶ A17	-0.2

Table 5

Test rope B — Max. %LMA in the major LMA rope sections

Rope section symbol	B2	B3	B6	B9	(B12+B13)
True LMA	unknown	-7.0	-7.6	-7.2	-7.7
Rotescograph					
Tests of April 5, 10, and 15, 1989					
5 mm/sec chart speed	-2.5	-6.2 (-0.8)*	-6.1 (-1.5)	-5.7 (-1.5)	-5.2 (-2.5)
1 mm/sec chart speed	-1.8	-4.6 (-2.4)	-4.6 (-3.0)	-4.5 (-2.7)	-4.0 (-3.7)
0.5 mm/sec chart speed	-1.8	-5.0 (-2.0)	-5.0 (-2.6)	-5.0 (-2.2)	-4.6 (-3.1)
LMA-250					
5 mm/sec chart speed					
Tests of 5.4.89	-3.3	-9.0 (+2.0)	-9.5 (+1.9)	-9.2 (+2.0)	-8.1 (+0.4)
Tests of 6.3.90	-3.2	-8.4 (+1.4)	-8.7 (+1.1)	-8.6 (+1.4)	-8.0 (+0.3)
Magnograph					
Tests of 4.4.89					
2.5% LMA/major chart division	-3.0	-7.5 (+0.5)	-8.0 (+0.4)	-8.0 (+0.8)	-7.5 (-0.2)
1.0% LMA/major chart division	-2.8	-7.2 (+0.2)	-7.6 (0.0)	-7.8 (+0.6)	-7.3 (-0.4)
Tests of 6.3.90					
2.5% LMA/major chart division	-2.6	-7.3 (+0.3)	-7.6 (0.0)	-7.8 (+0.6)	-7.0 (-0.7)
1.0% LMA/major chart division	-2.6	-6.8 (-0.2)	-6.8 (-0.8)	-7.1 (-0.1)	-6.7 (-1.0)

*: bracketed values = accuracy = true %LMA - NDT %LMA

Table 6

Test rope B — Max. %LMA inbetween the major LMA rope sections

Rope section symbol	B2-B3	B3-B6	B6-B9	B9-B12	B13-B15
True LMA	0.0	0.0	0.0	0.0	0.0
Rotescograph					
Tests of April 5, 10, and 15, 1989					
5 mm/sec chart speed	-0.4	-0.4	0.0	+0.5	-0.8
1 mm/sec chart speed	-0.4	-0.3	0.0	+0.4	+0.4
0.5 mm/sec chart speed	-0.5	-0.6	-0.6	-0.2	-0.7
LMA-250					
5 mm/sec chart speed					
Tests of 5.4.89	-0.5	-1.0	-0.8	-0.2	0.0
Tests of 6.3.90	-0.4	-0.8	-0.6	0.0	0.0
Magnograph					
Tests of 4.4.89					
2.5% LMA/major chart division	-0.5	-1.0	-1.0	0.0	0.0
1.0% LMA/major chart division	-0.7	-0.7	-0.6	0.0	0.0
Tests of 6.3.90					
2.5% LMA/major chart division	-0.5	-1.0	-0.8	0.0	0.0
1.0% LMA/major chart division	-0.7	-0.6	-0.6	-0.1	0.0

Table 7

Test rope B — %LMA results at rope core sections with metal fillers

Rope section symbol	B12–B13 at interface	B15	B16
True LMA	+3.0	+11.0	+2.0
Rotescograph			
Tests of April 5, 10, and 15, 1989			
5 mm/sec chart speed	0.7	+1.6	+0.2
1 mm/sec chart speed	0.5	+1.5	+0.2
0.5 mm/sec chart speed	0.4	+1.1	+0.2
LMA-250			
5 mm/sec chart speed			
Tests of 5.4.89	1.0	+2.0	0.0
Tests of 6.3.90	1.2	+2.2	0.0
Magnograph			
Tests of 4.4.89			
2.5% LMA/major chart division	0.5	+1.0	0.0
1.0% LMA/major chart division	0.8	+1.0	0.0
Tests of 6.3.90			
2.5% LMA/major chart division	0.8	+1.2	0.0
1.0% LMA/major chart division	0.7	+1.1	0.0

Table 8 — Test rope B

Shift of 100% LMA ref. level along "defective" rope section

Test details	see Figure No.	Sequence of events B1 ⟺ B17	% shift
Rotescograph			
5 mm/sec chart speed	2a	B1 ⟵ B17	+1.5
1 mm/sec chart speed	2b	B1 ⟶ B17	-1.0
0.5 mm/sec chart speed	2c	B1 ⟵ B17	-0.4
LMA-250			
5 mm/sec chart speed			
Tests of 5.4.89	4a	B1 ⟵ B17	+0.5
Tests of 6.3.90	6	B1 ⟶ B17	-0.8
Magnograph			
Tests of 4.4.89			
2.5% LMA/major chart division	8a	B1 ⟵ B17	+0.2
1.0% LMA/major chart division	$8b_1$	B1 ⟶ B17	nil
Tests of 6.3.90			
2.5% LMA/major chart division	10b	B1 ⟶ B17	+0.2
1.0% LMA/major chart division	10a	B1 ⟶ B17	+0.2

Table 9

Droop testing the LMA-250 instrument
October, 1989

Test No.	Test procedure	LMA gain potentiometer setting	Migration rate
1	Insert small diam elevator rope sample into empty head	1.00	−0.14% per min
2	Insert two strands of elevator rope sample into empty head	5.00	−0.57% per min
3	Insert one strand of elevator rope sample into empty head	9.00	−1.17% per min
4	Remove one strand of elevator rope sample from otherwise empty head	9.00	+0.70% per min
5	Insert elevator rope sample, plus one extra strand, into empty head. Reset machine, and remove extra strand	9.00	+0.71% per min

Table 10

Fig. 32a — Comparative Magnograph^{TM} and LMA-Test^{TM} instrument chart-readings

Rope section	LMA chart-reading	
	Magnograph^{TM}	LMA-Test^{TM}
Splice	+13.0%	+14.5%
Short inter-splice	+2.5%	0.0%
Long inter-splice	0.0%	0.0%
1 wire missing	-1.5%	-2.0%
2 wires missing	-4.0%	-4.0%
3 wires missing	-6.0%	-6.0%
1 broken wire	-0.5%	-1.0%
2 broken wires	-1.0%	-2.5%
3 broken wires	-1.5%	-3.5%

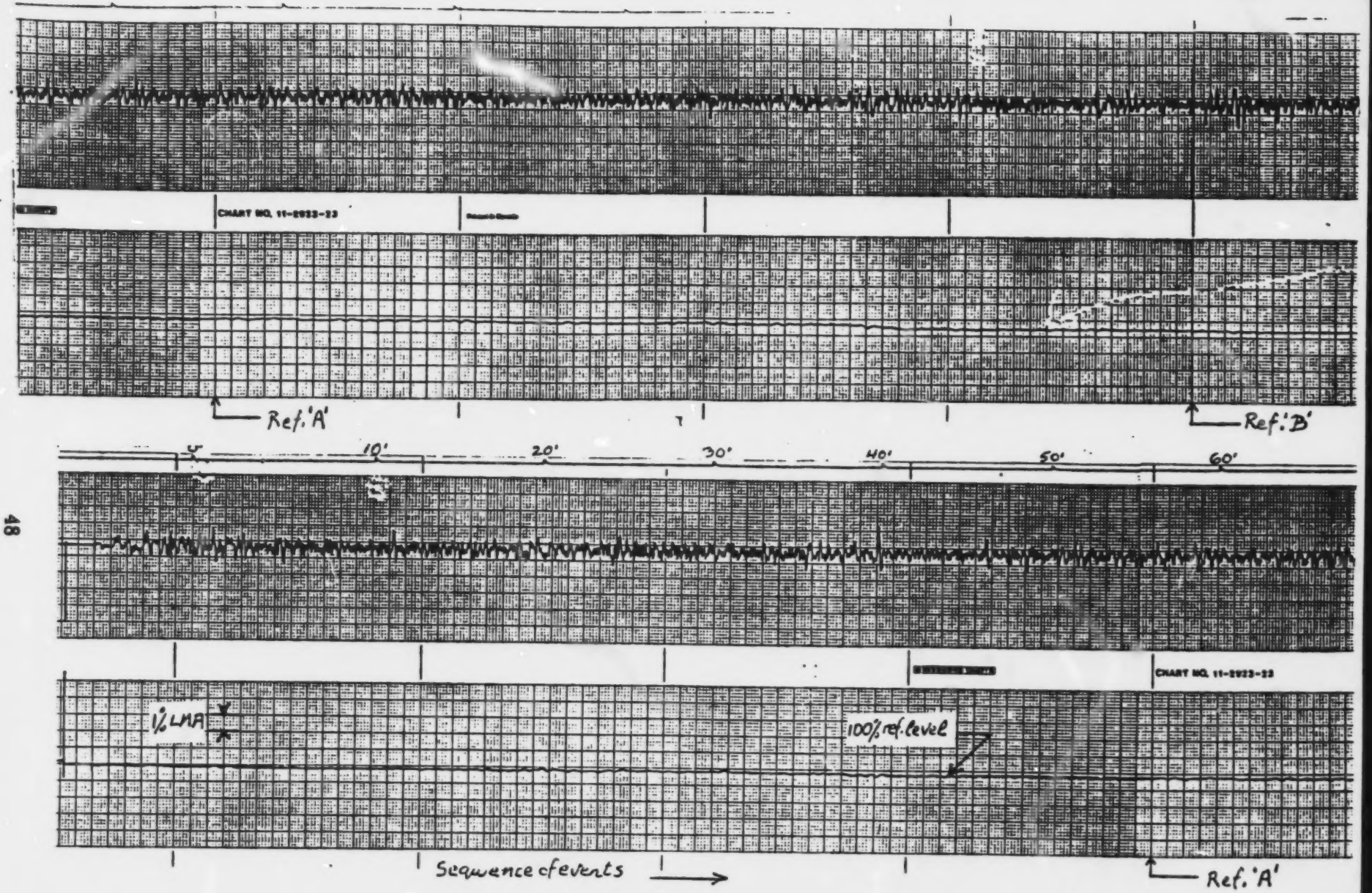

Fig. 1a — Test-rope 'A' with Rotescograph, 5 mm/sec chart speed, April 5, 1989

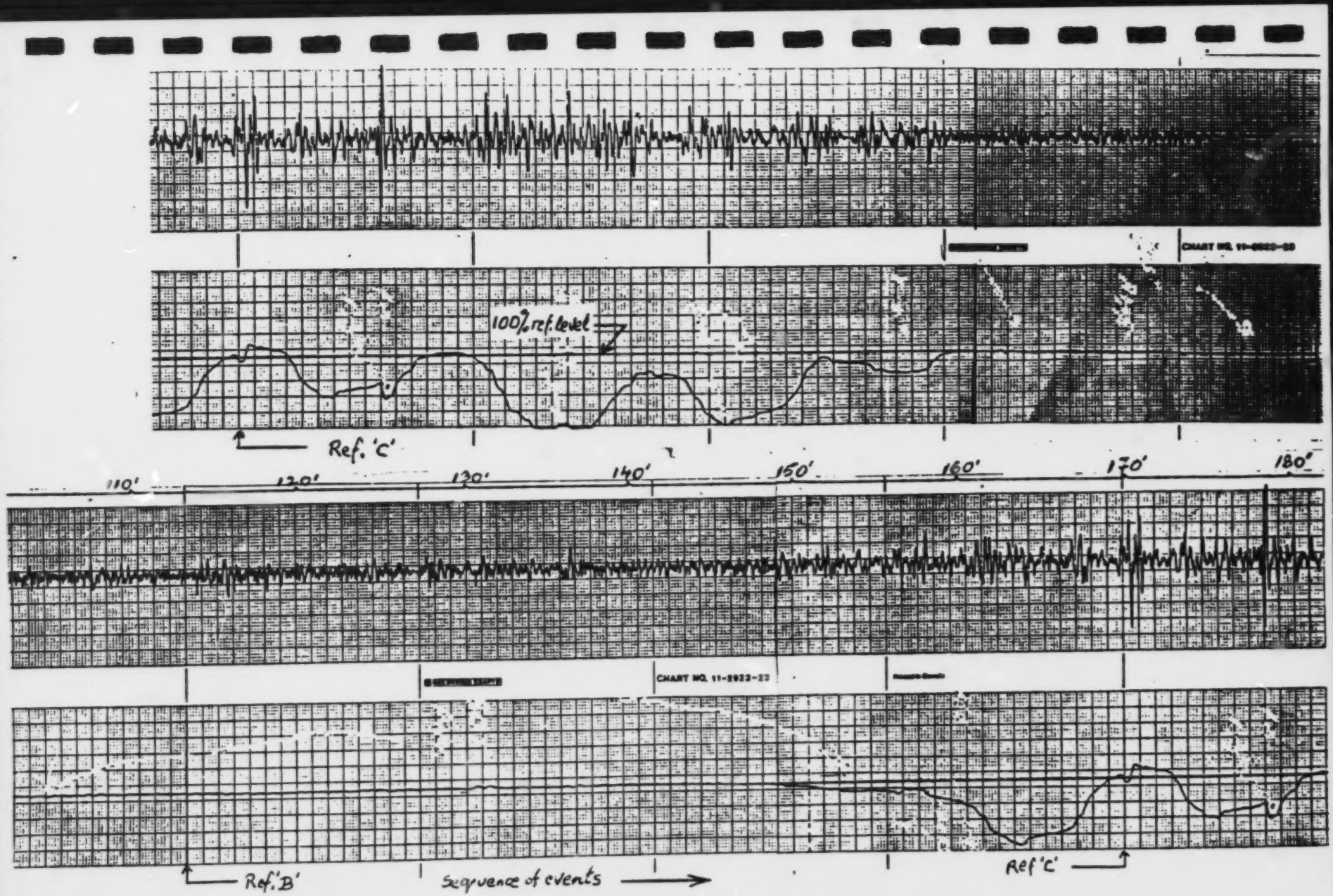

Fig. 1a (continued) — Test-rope 'A' with Rotescograph, 5 mm/sec chart speed, April 5, 1989

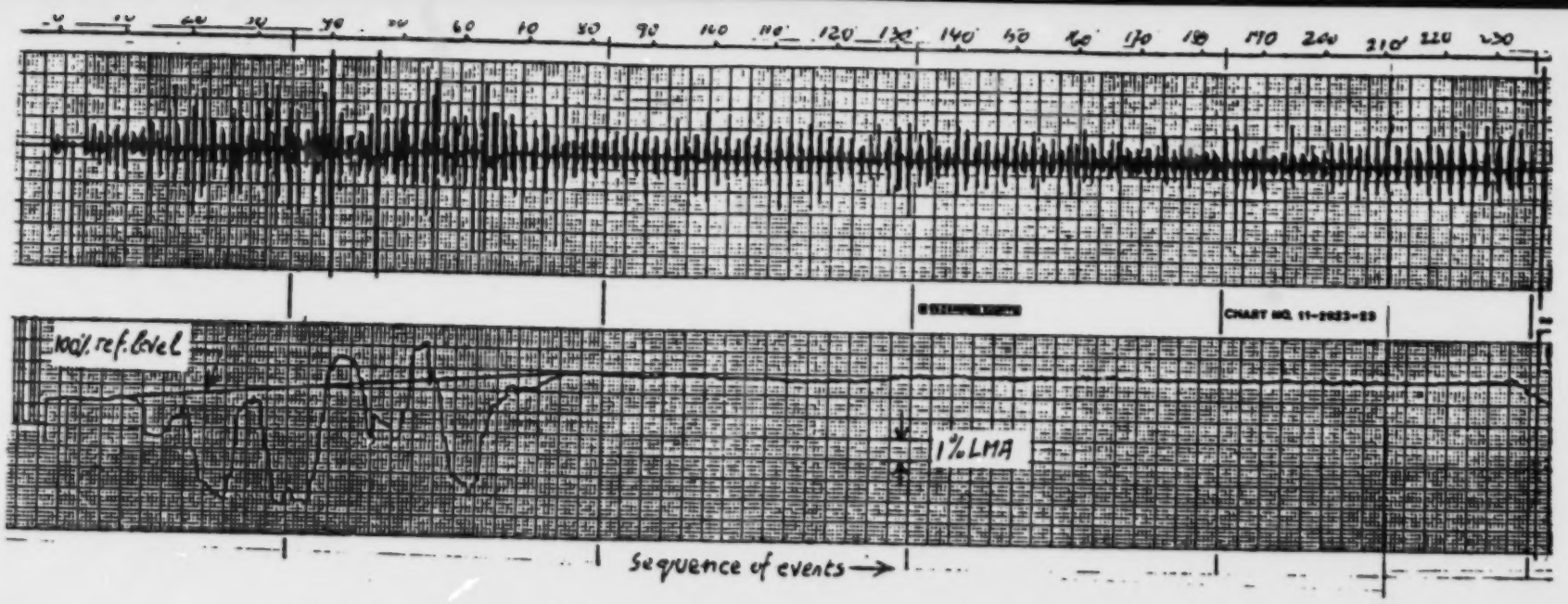

Fig. 1b — Test-rope 'A' with Rotescograph, 1 mm/sec chart speed, April 15, 1989

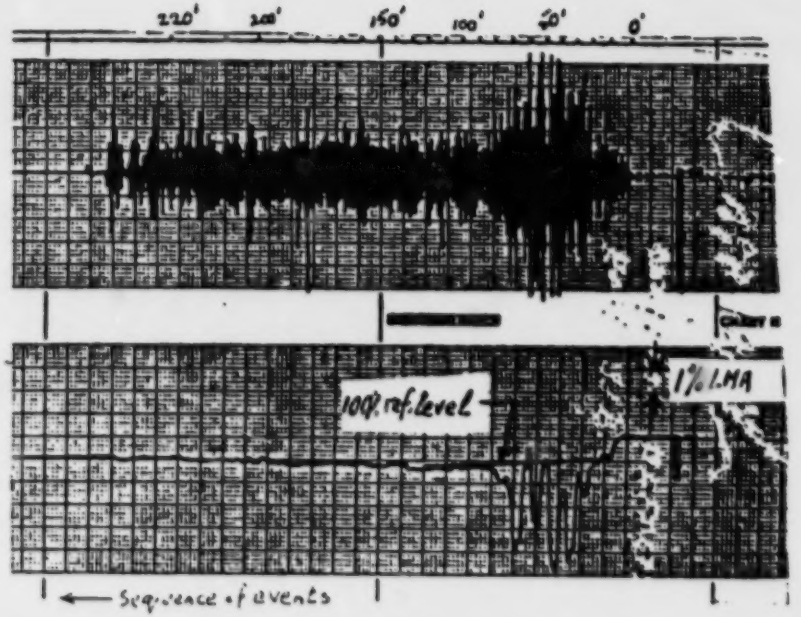

Fig. 1c — Test-rope 'A' with Rotescograph,

0.5 mm/sec chart speed, April 10, 1989

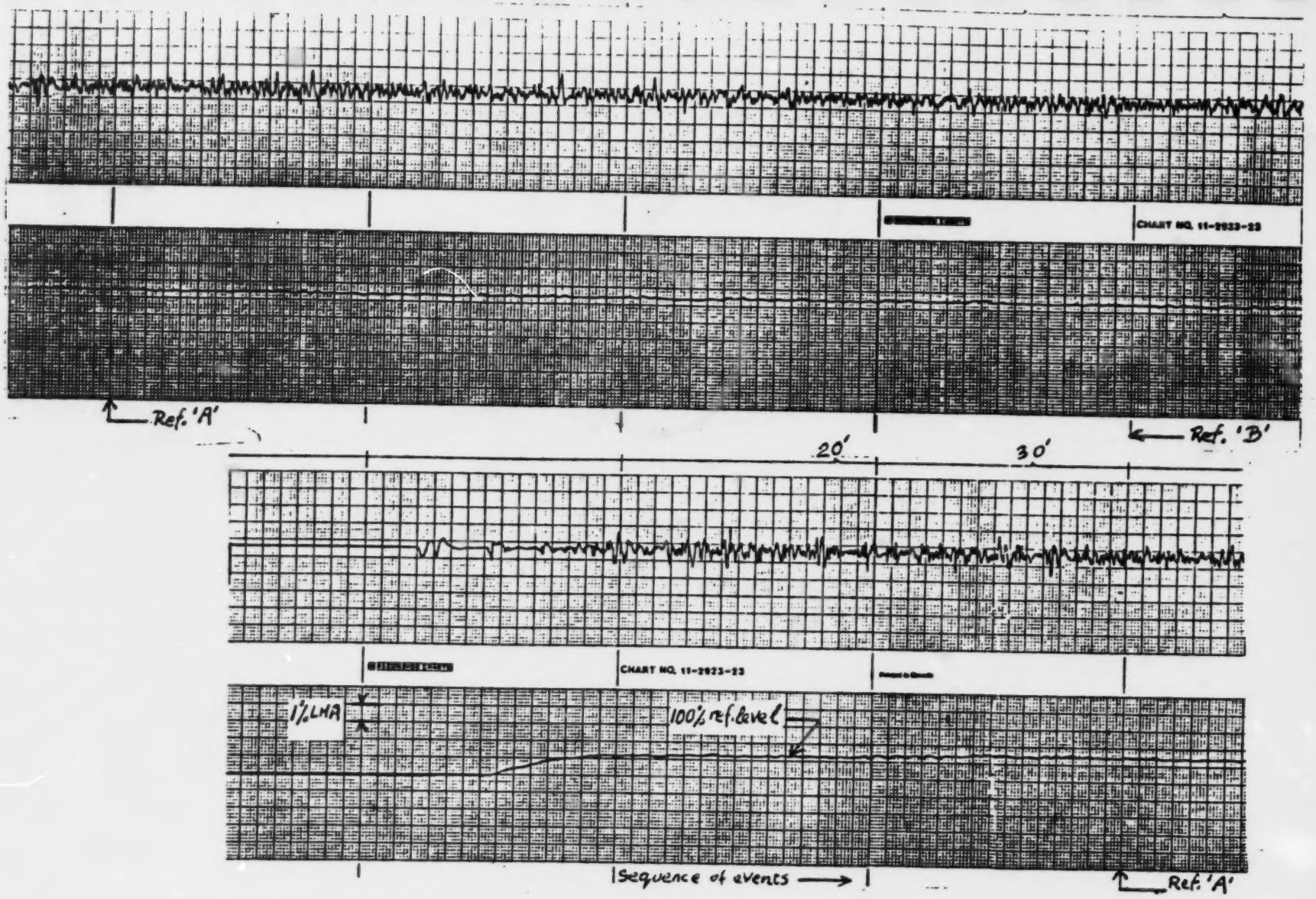

Fig. 2a — Test-rope 'B' with Rotescograph, 5 mm/sec chart speed, April 5, 1989

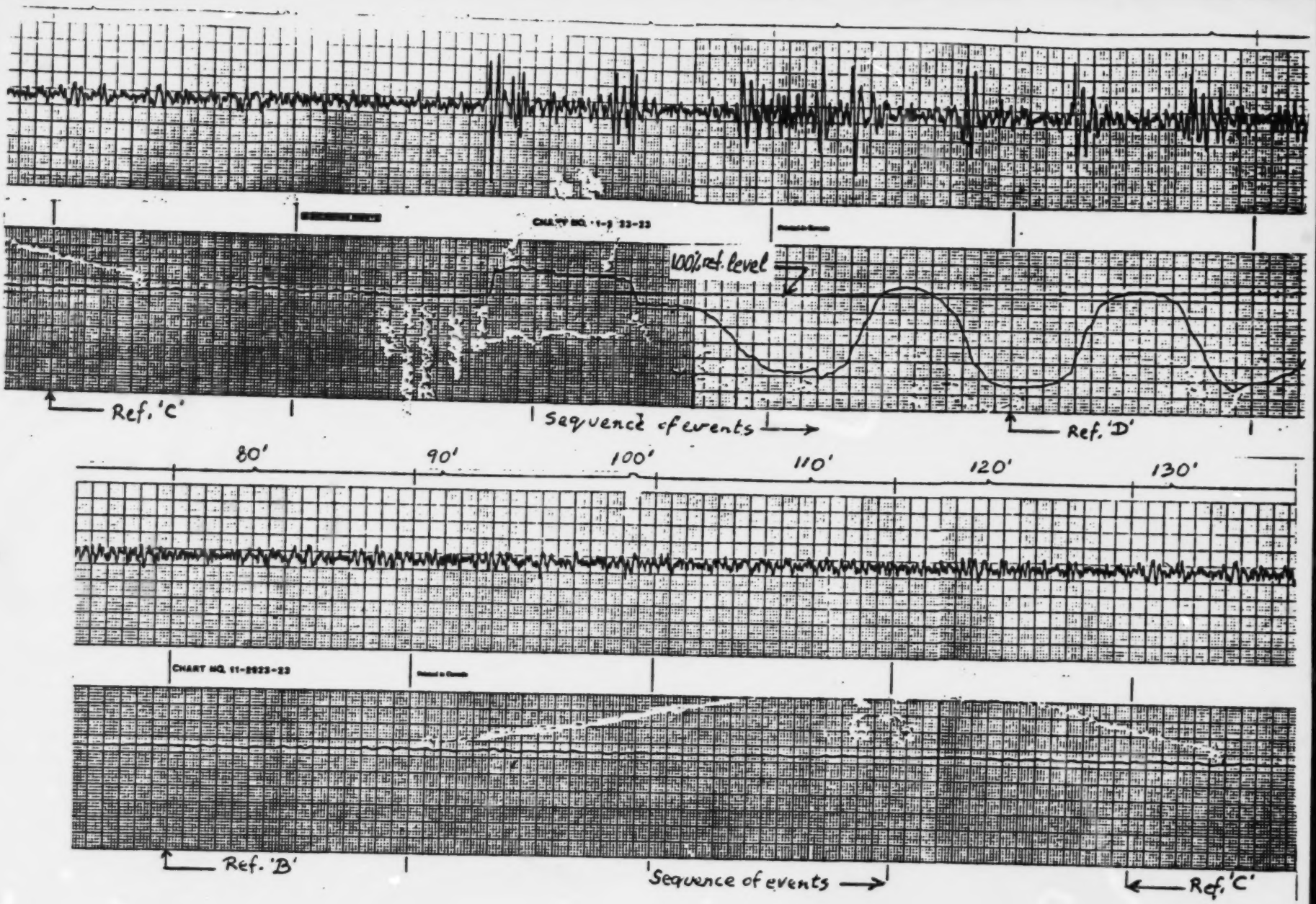

Fig. 2a (continued) — Test-rope 'B' with Rotescograph, 5 mm/sec chart speed, April 5, 1989

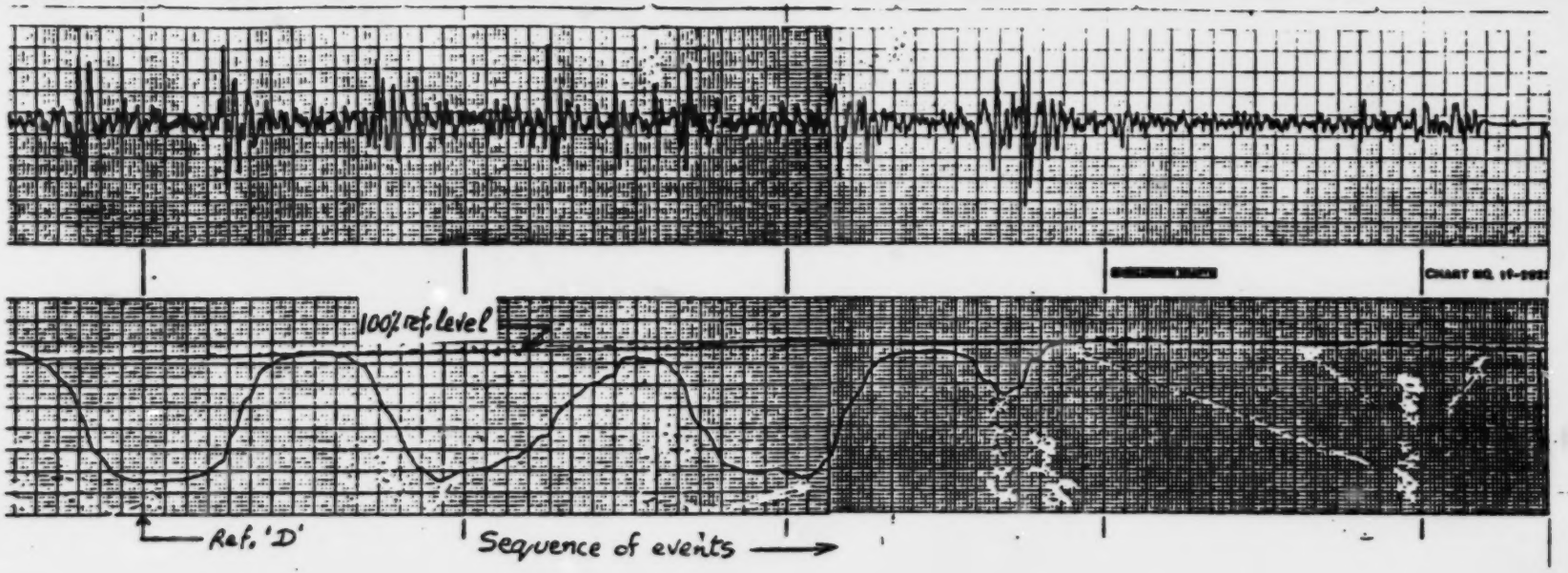

Fig. 2a (continued) — Test-rope 'B' with Rotescograph, 5 mm/sec chart speed, April 5, 1989

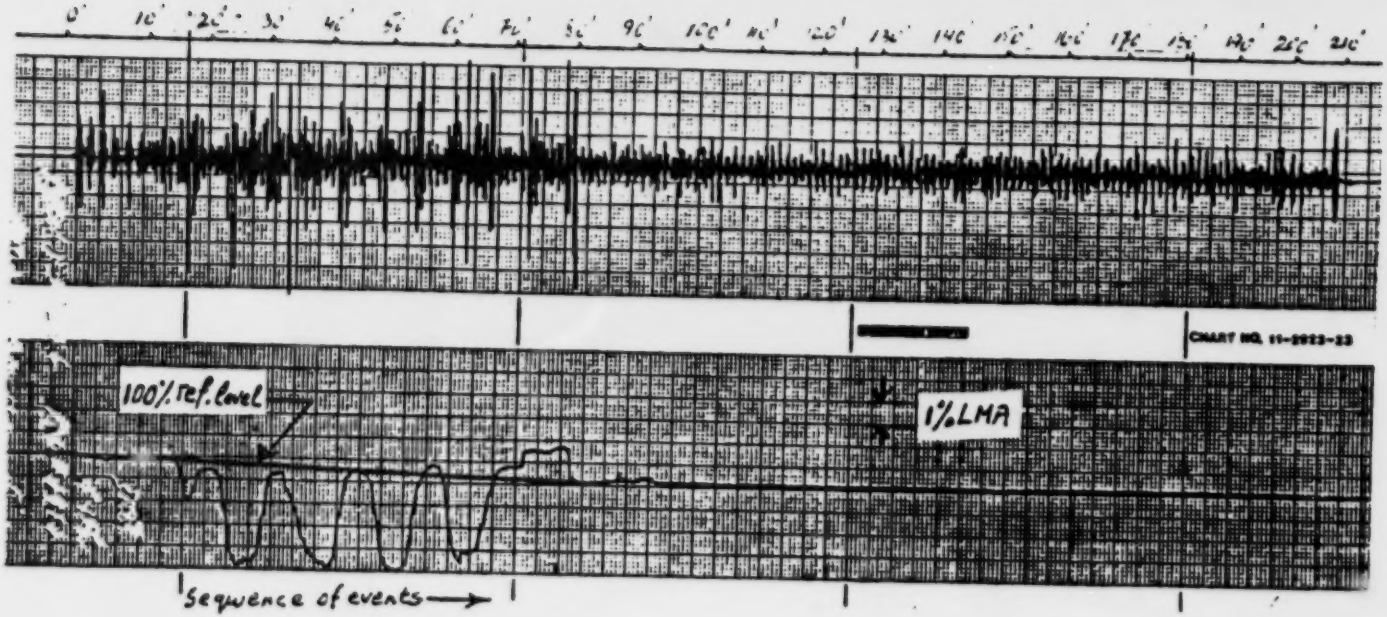

Fig. 2b — Test-rope 'B' with Rotescograph, 1 mm/sec chart speed, April 15, 1989

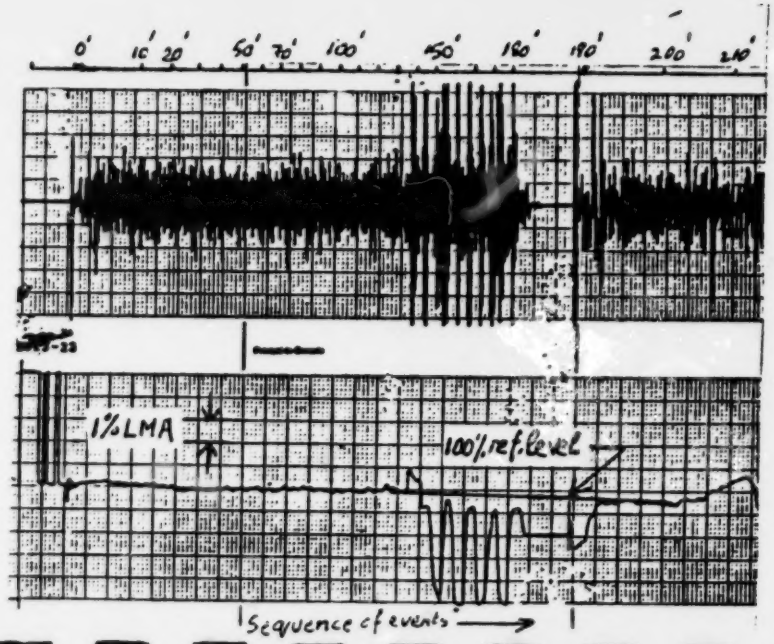

Fig. 2c — Test-rope 'B' with Rotescograph,

0.5 mm/sec chart speed, April 10, 1989

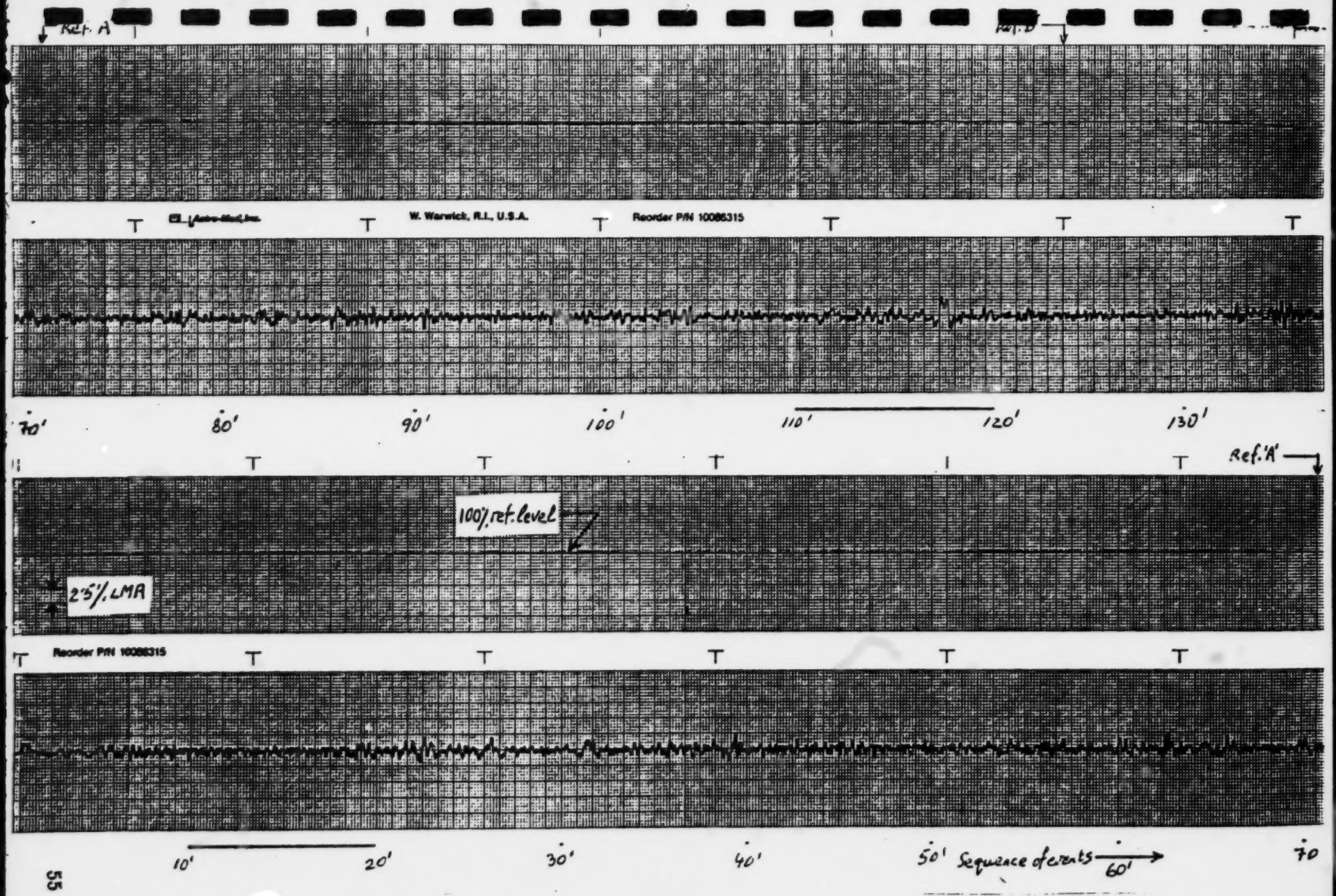

Fig. 3 — Test-rope 'A' with LMA-250, 5 mm/sec chart speed, April 5, 1989

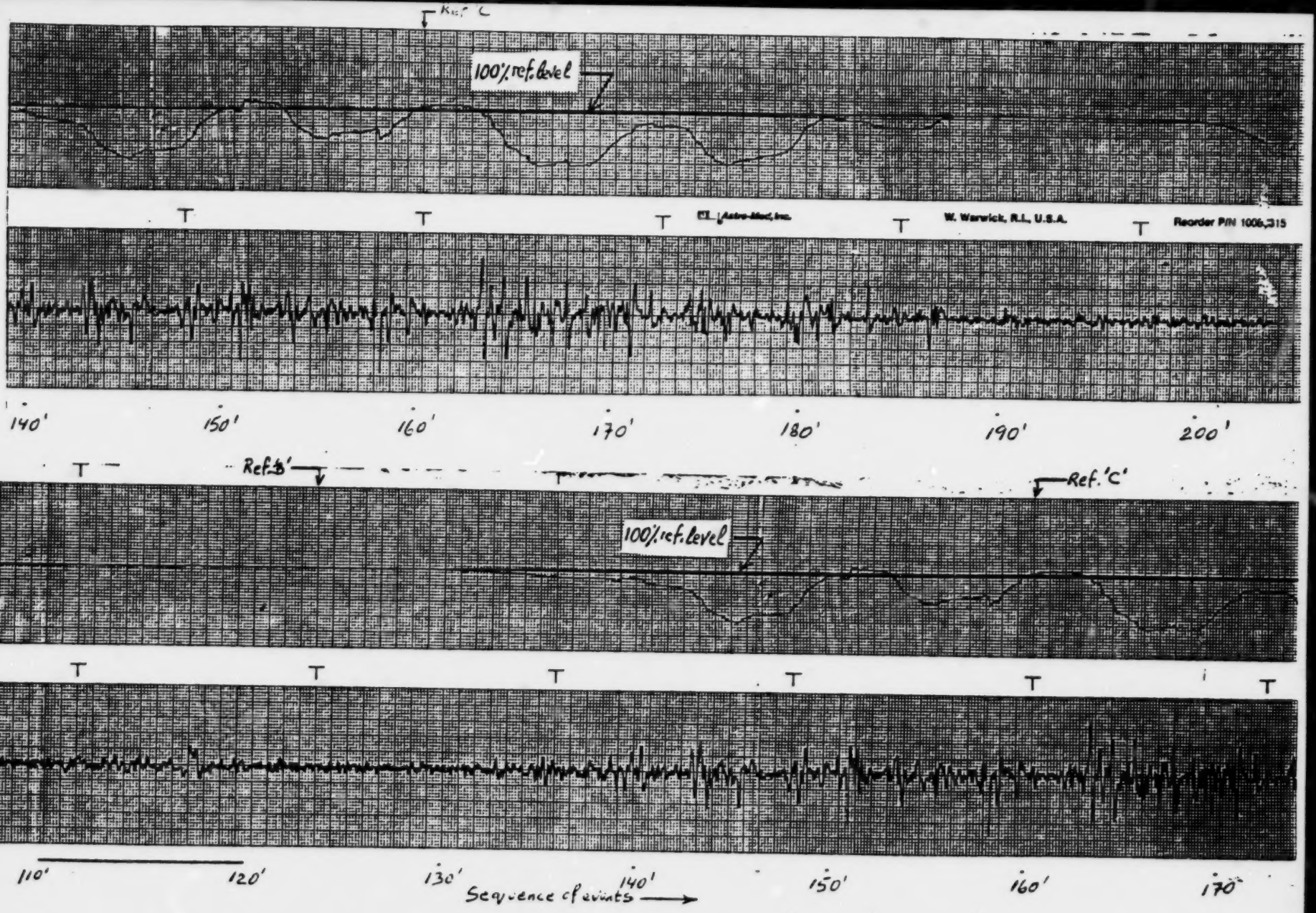

Fig. 3 (continued) — Test-rope 'A' with LMA-250, 5 mm/sec chart speed, April 5, 1989

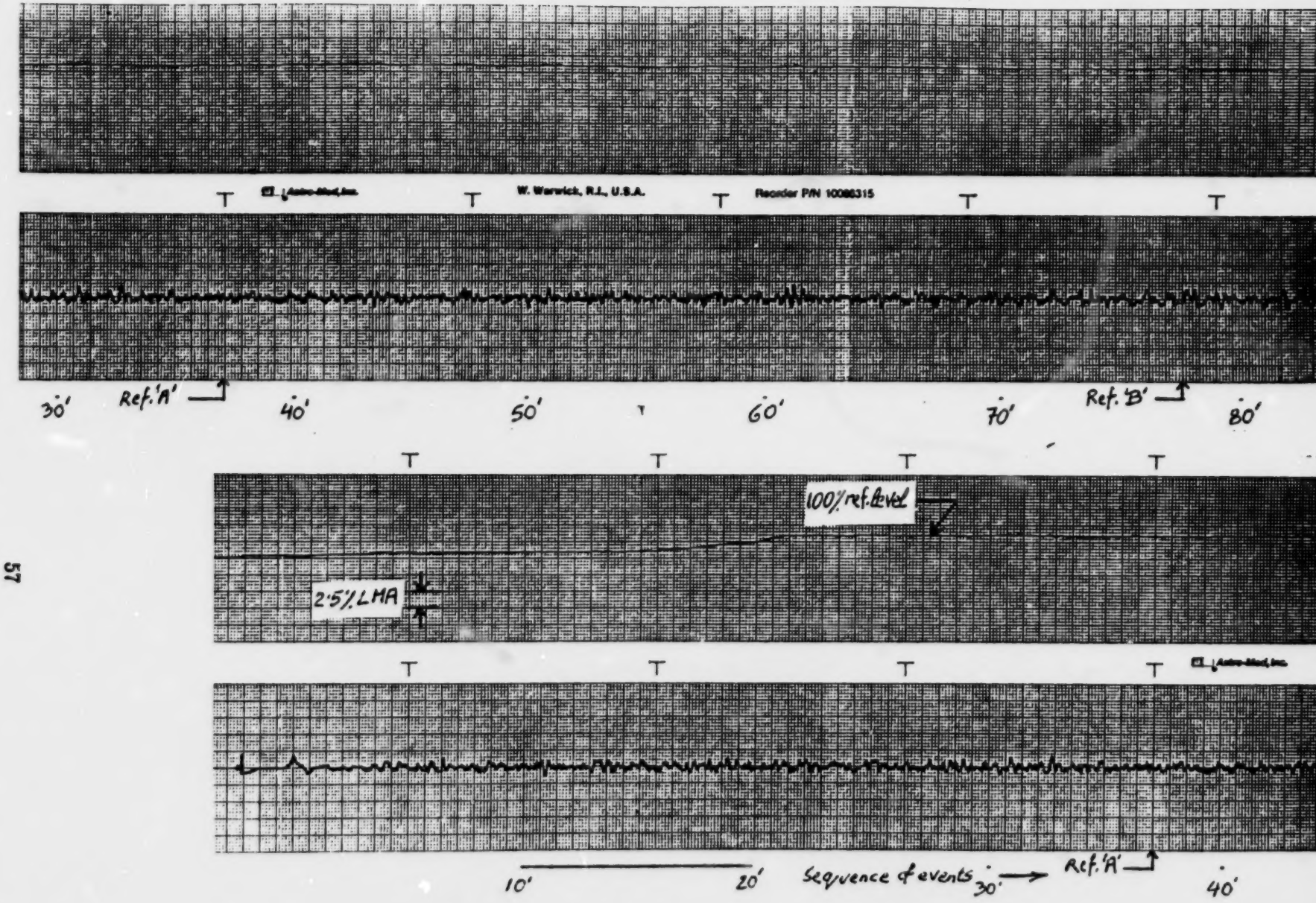

Fig. 4a — Test-rope 'B' with LMA-250, second run, 5 mm/sec chart speed, April 5, 1989

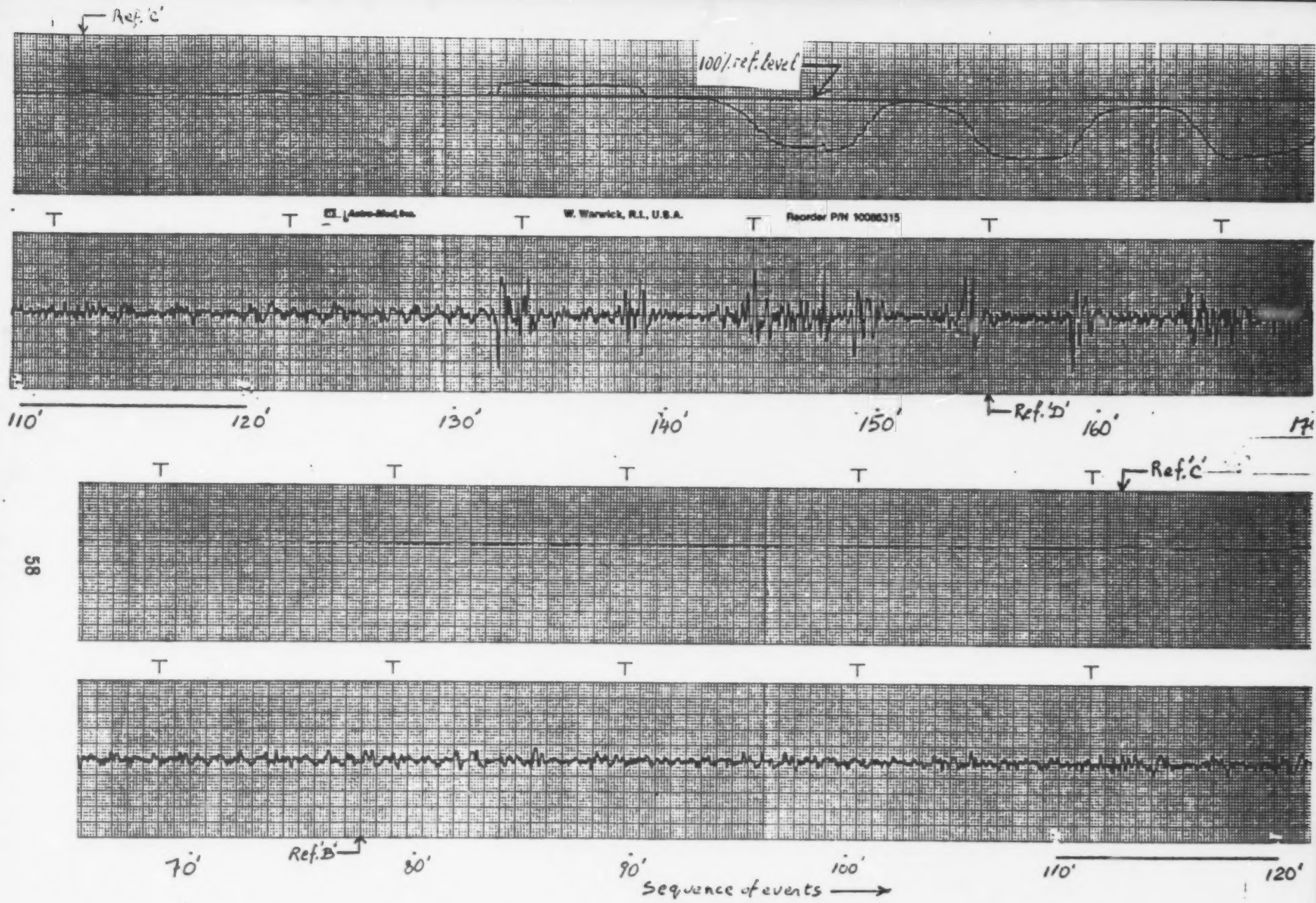

Fig. 4a (continued) — Test-rope 'B' with LMA-250, second run, 5 mm/sec chart speed, April 5, 1989

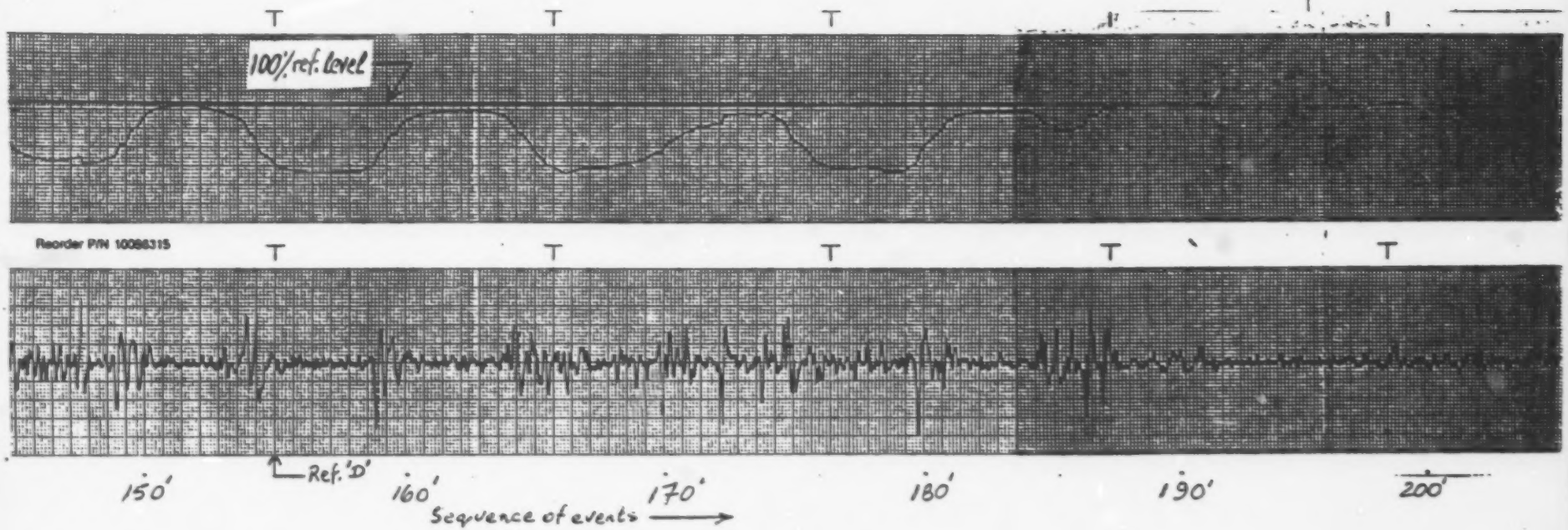

Fig. 4a (continued) — Test-rope 'B' with LMA-250, second run, 5 mm/sec chart speed, April 5, 1989

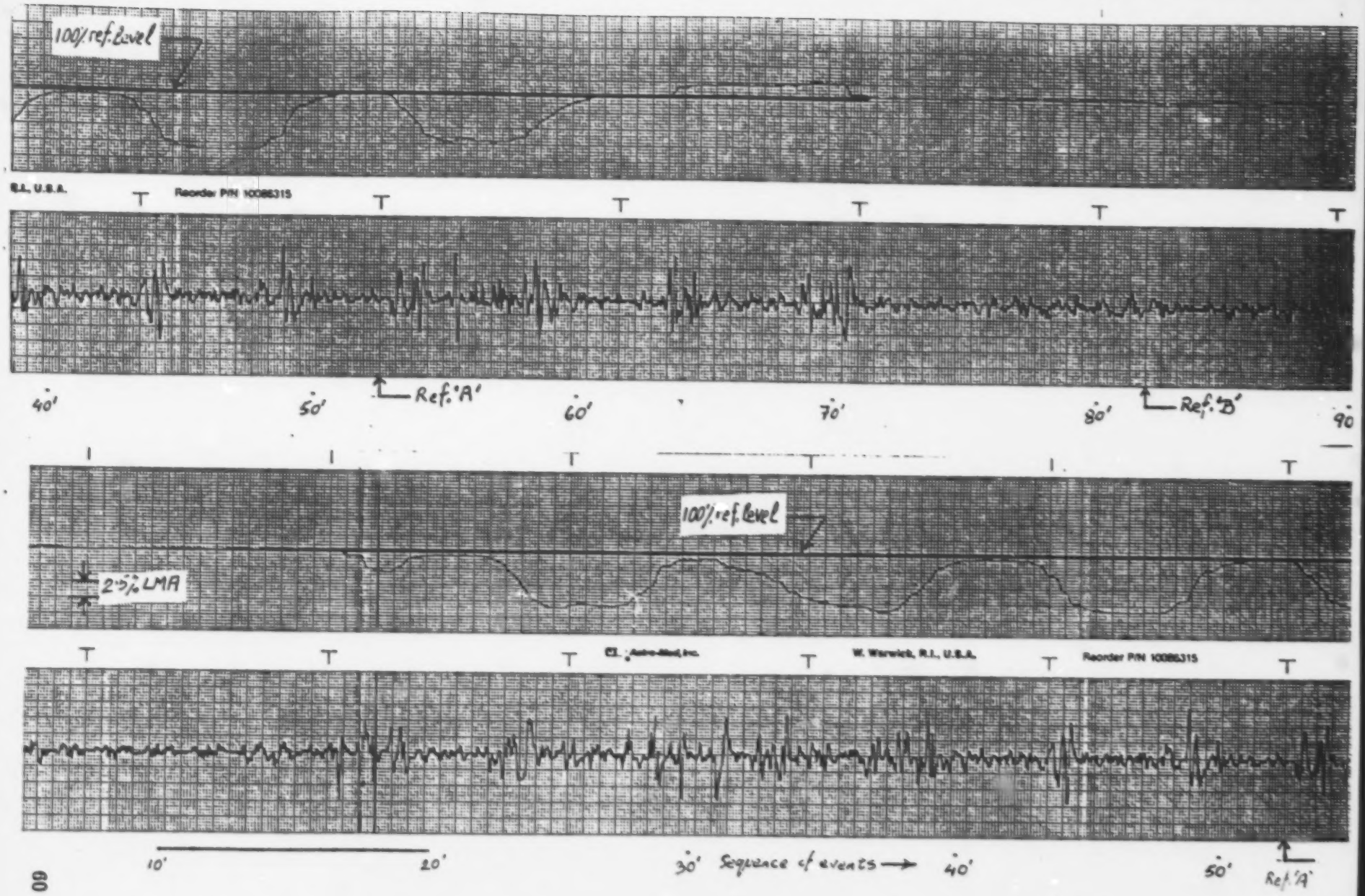

Fig. 4b — Test-rope 'B' with LMA-250, first run, 5 mm/sec chart speed, April 5, 1989

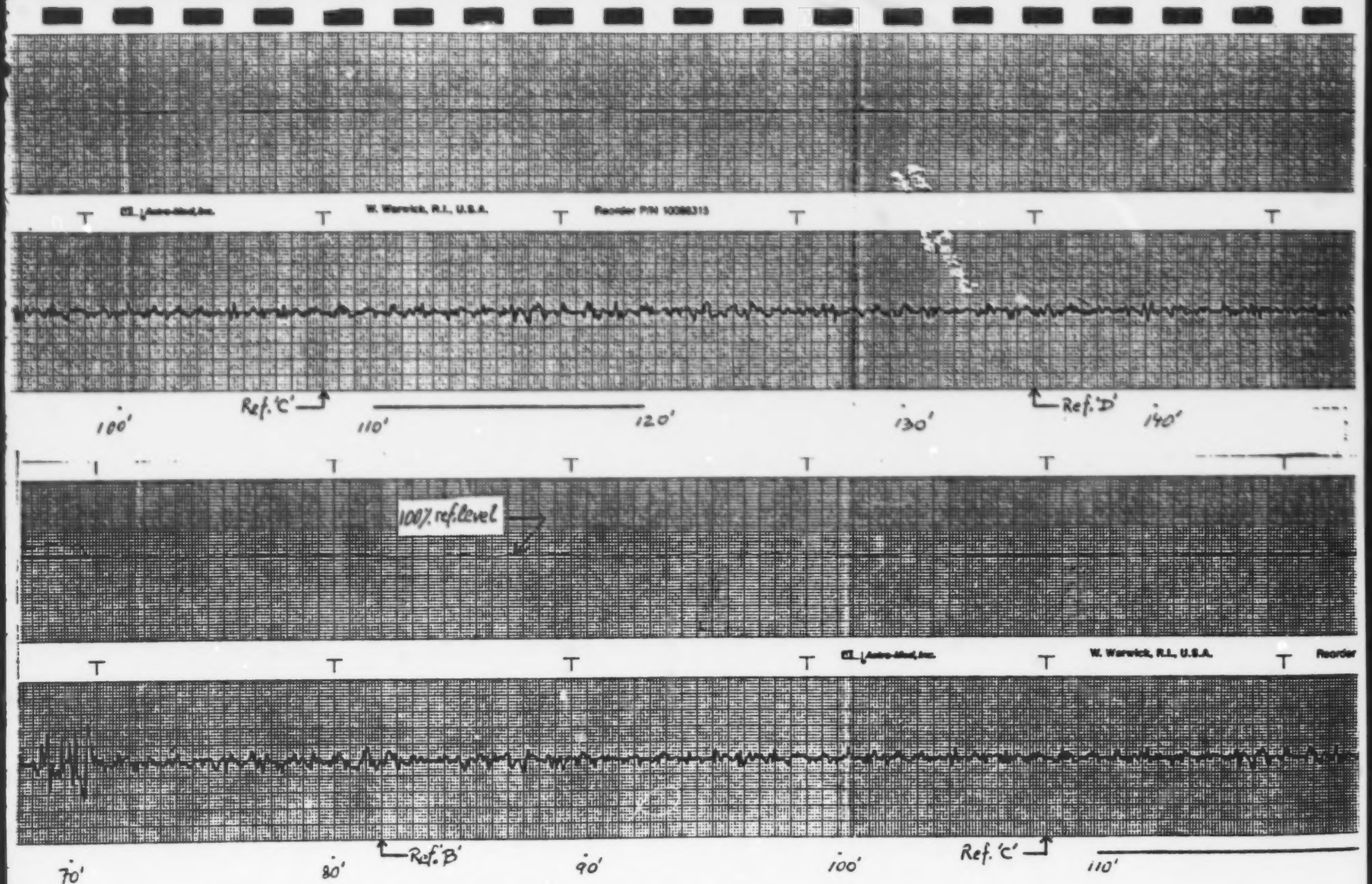

Fig. 4b (continued) — Test-rope 'B' with LMA-250, first run, 5 mm/sec chart speed, April 5, 1989

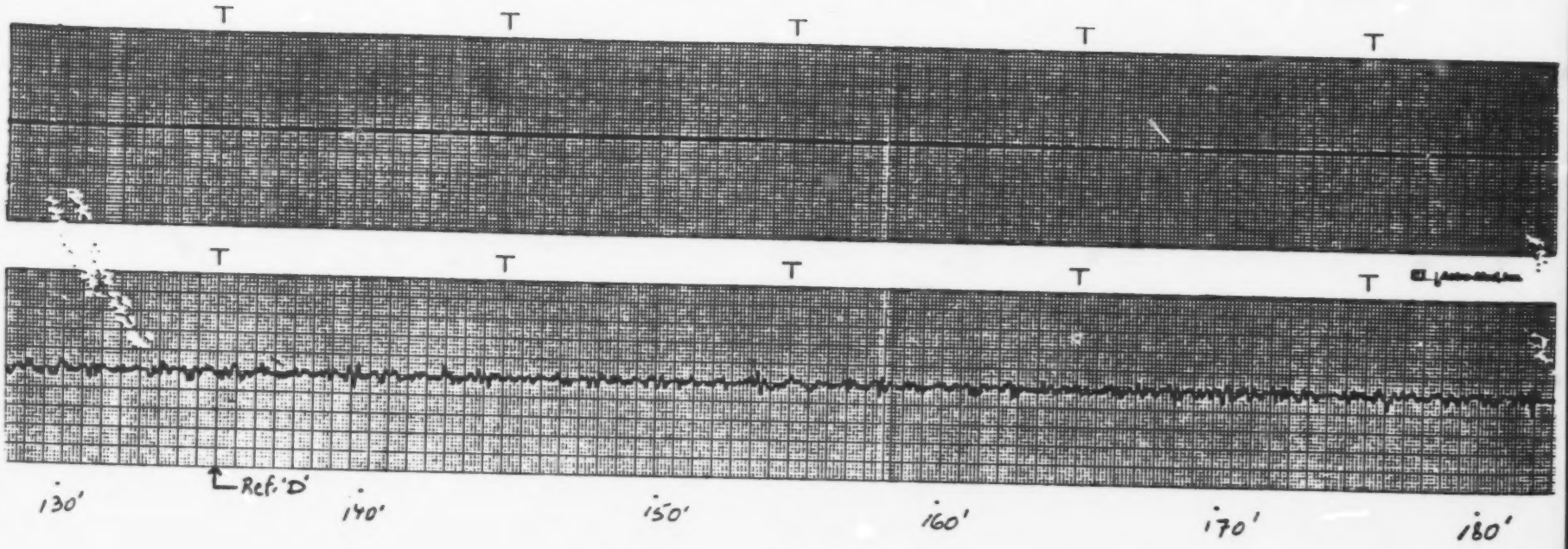

Fig. 4b (continued) — Test-rope 'B' with LMA-250, first run, 5 mm/sec chart speed, April 5, 1989

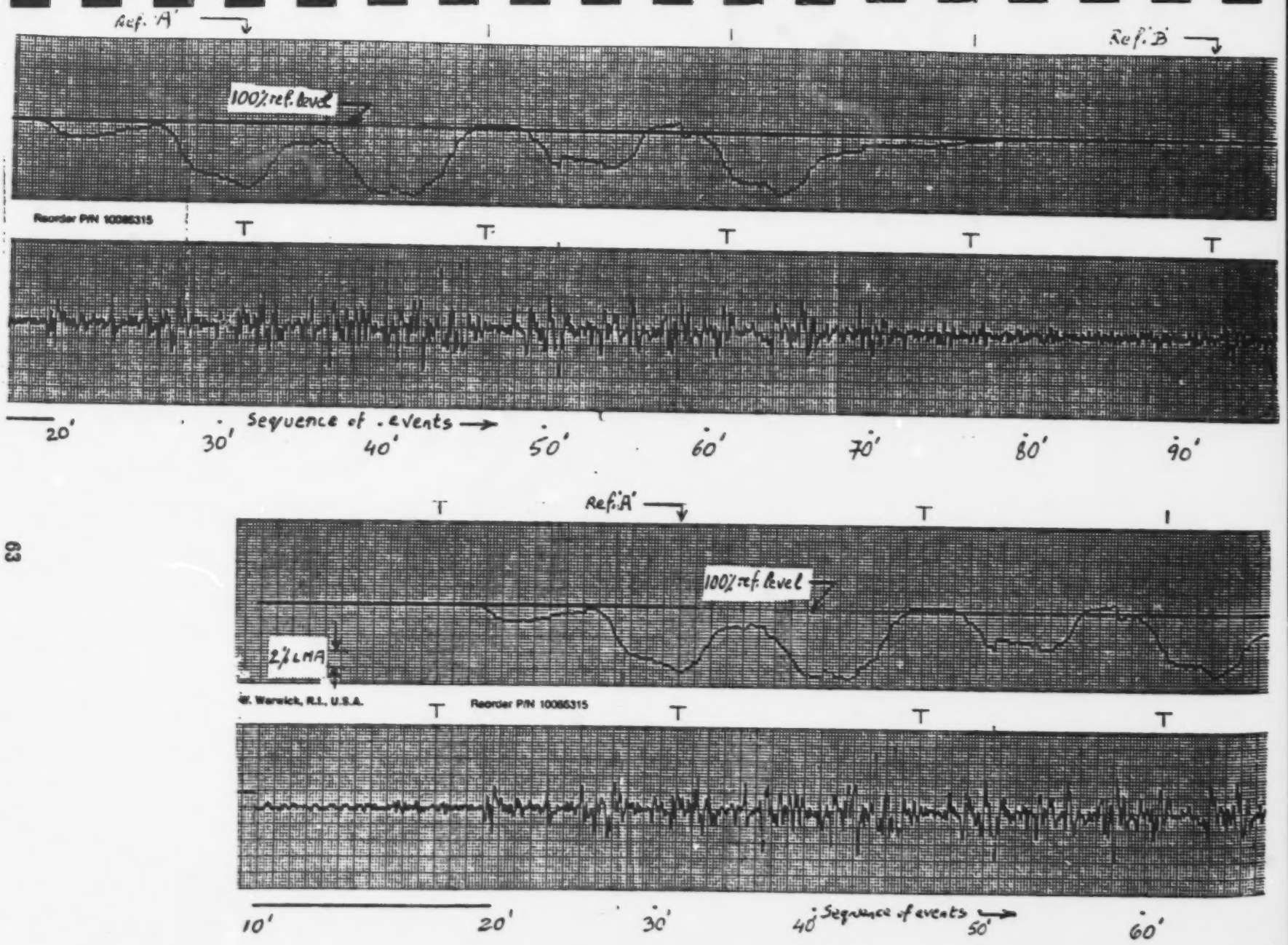

Fig. 5 — Test-rope 'A' with LMA-250, 5 mm/sec chart speed, March 6, 1990

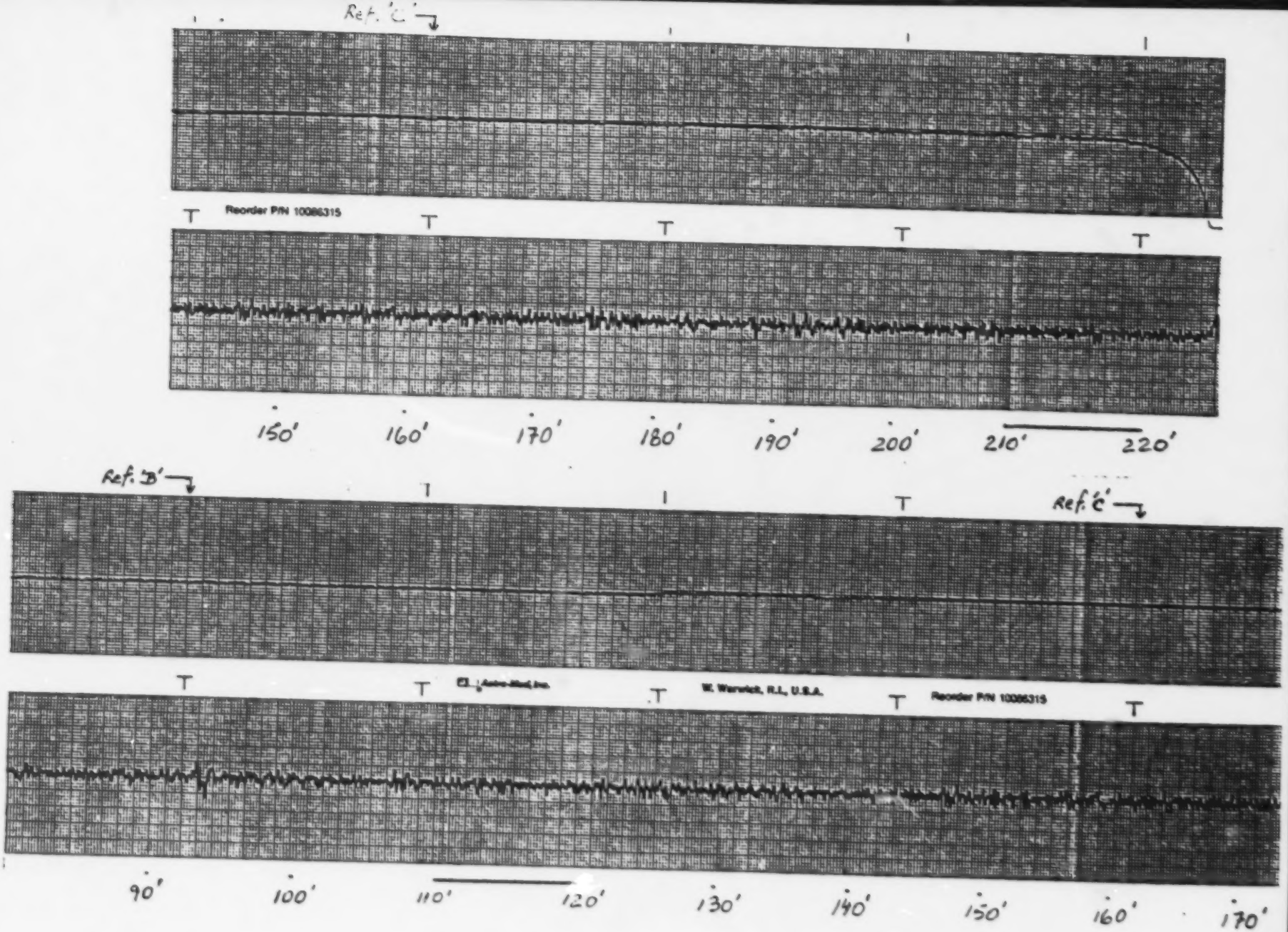

Fig. 5 (continued) — Test-rope 'A' with LMA-250, 5 mm/sec chart speed, March 6, 1990

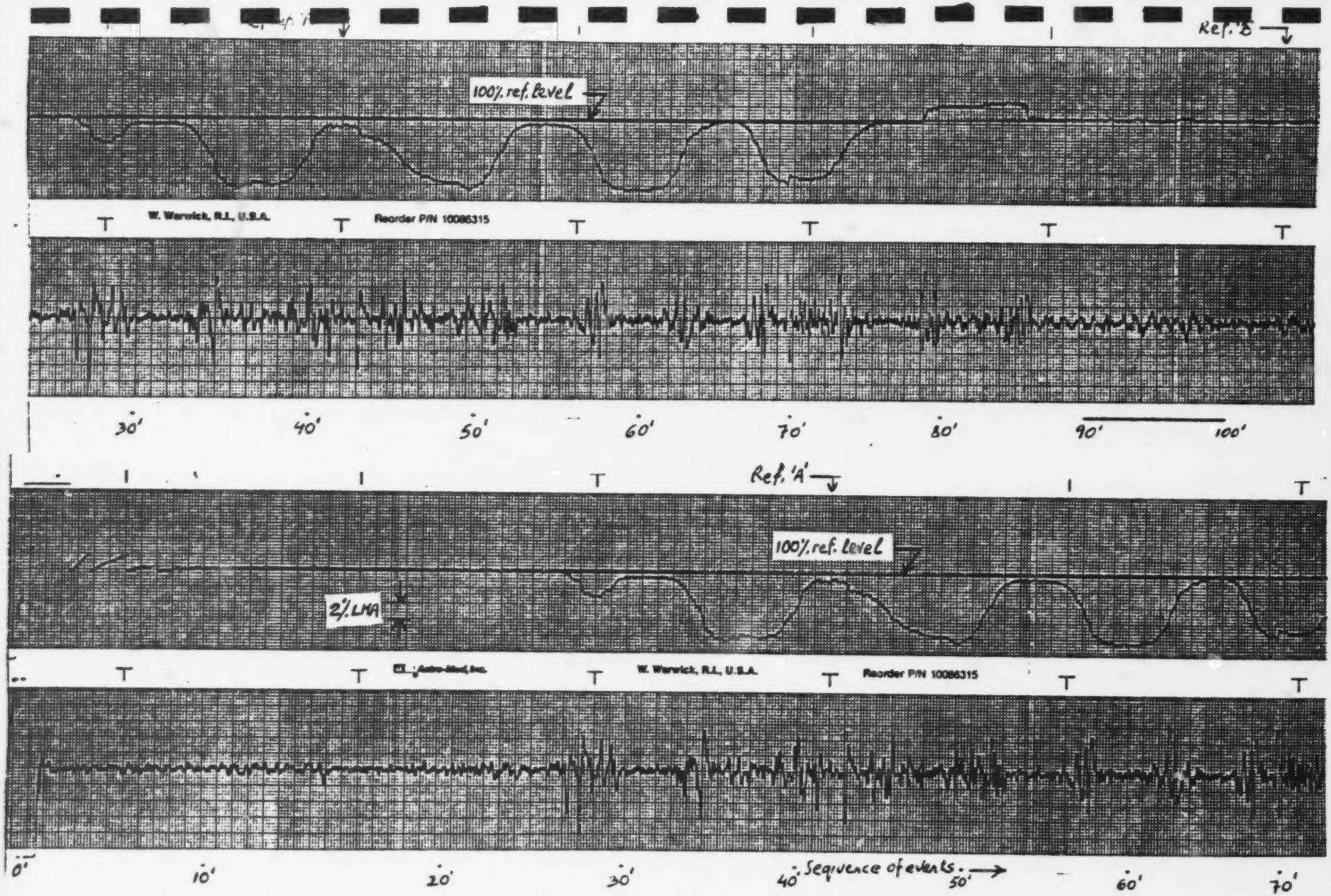

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Fig. 6 — Test-rope 'B' with LMA-250, 5 mm/sec chart speed, March 6, 1990

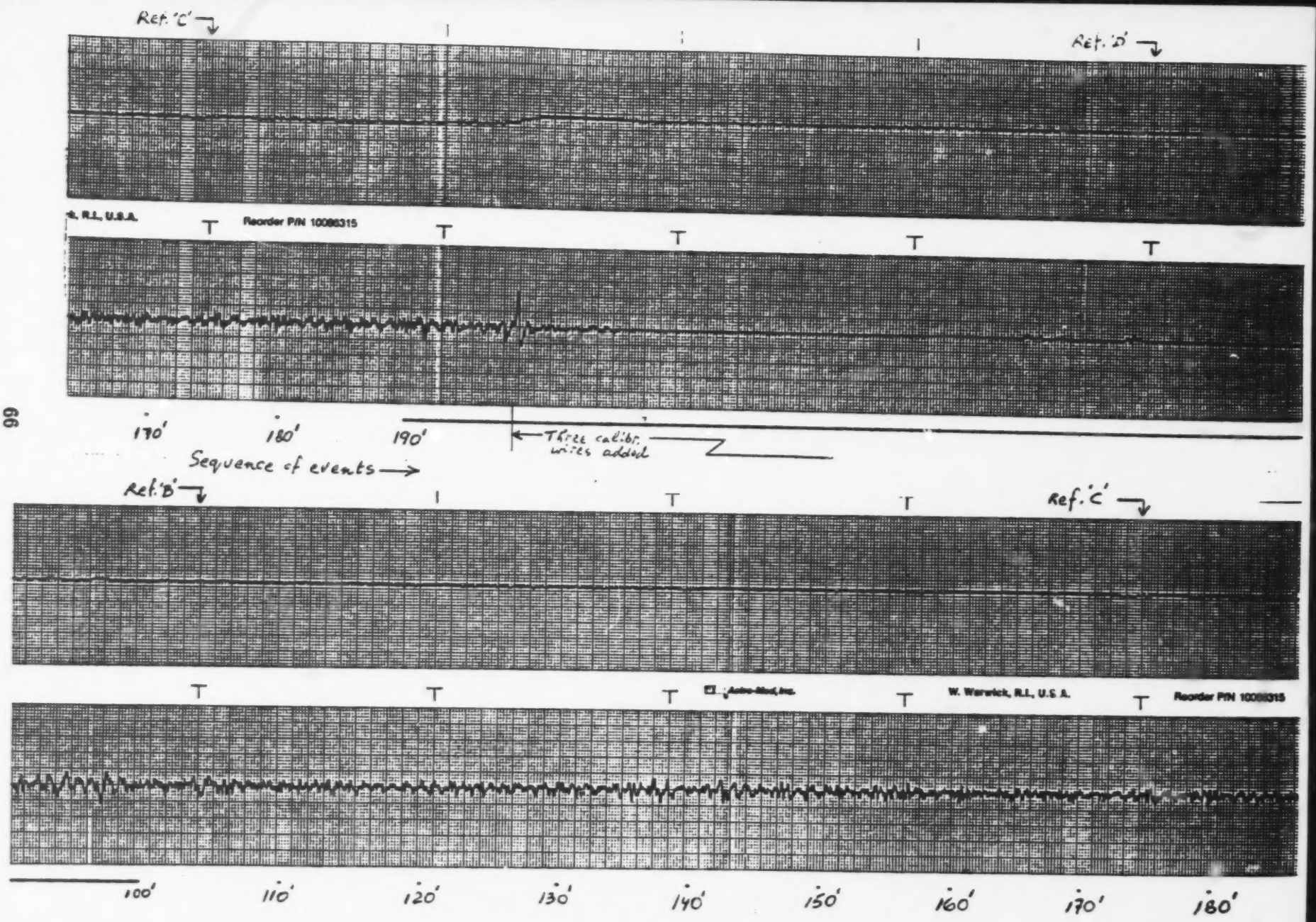


Fig. 6 (continued) — Test-rope 'B' with LMA-250, 5 mm/sec chart speed, March 6, 1990

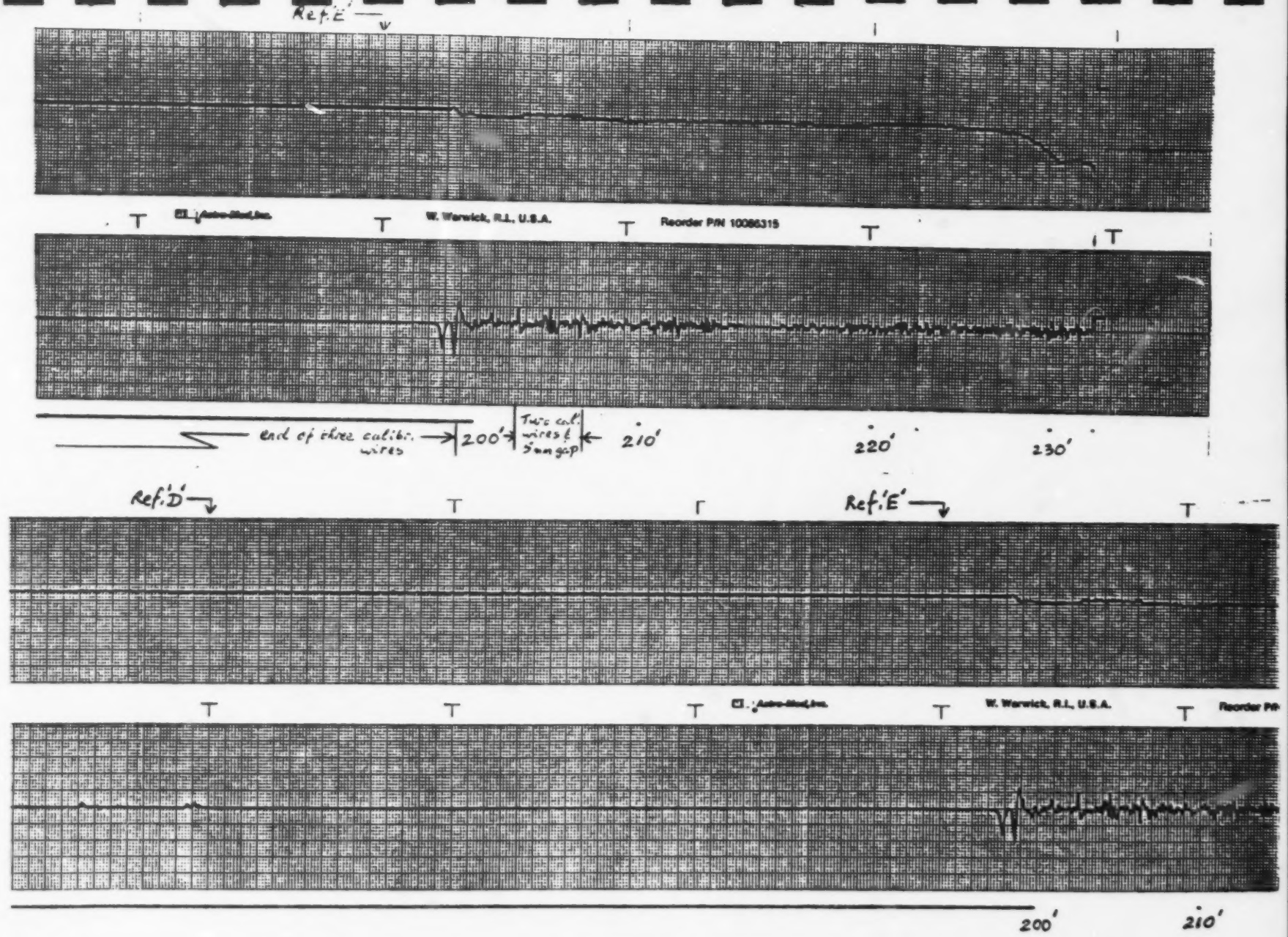


Fig. 6 (continued) — Test-rope 'B' with LMA-250, 5 mm/sec chart speed, March 6, 1990

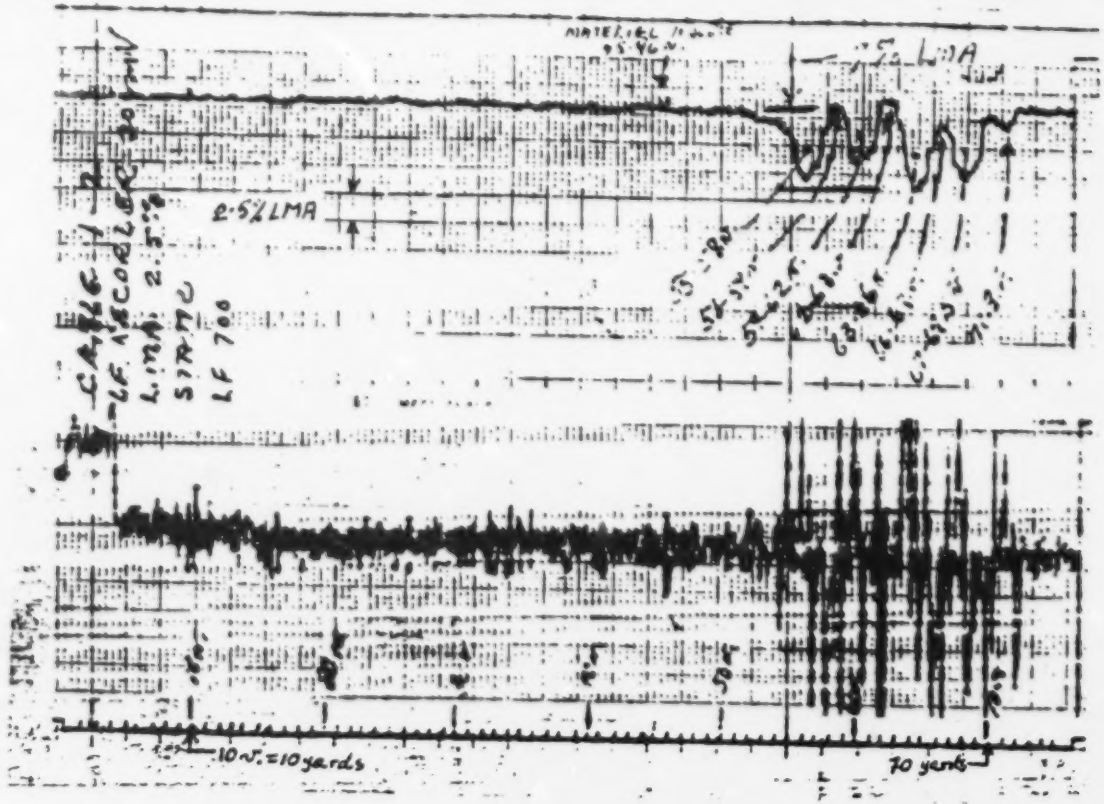


Fig. 7a — Test-rope 'A' with Magnograph, April 4, 1989

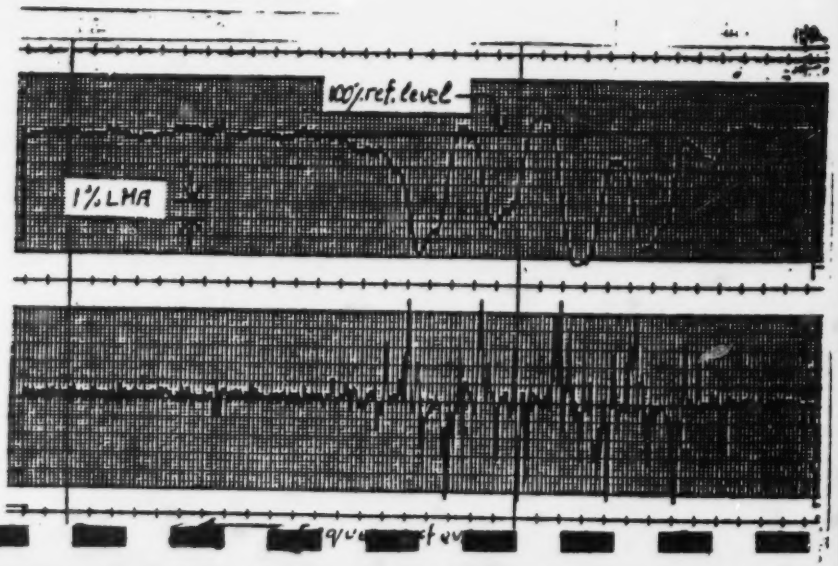


Fig. $7b_2$ — Test-rope 'A' with Magnograph, April 4, 1989

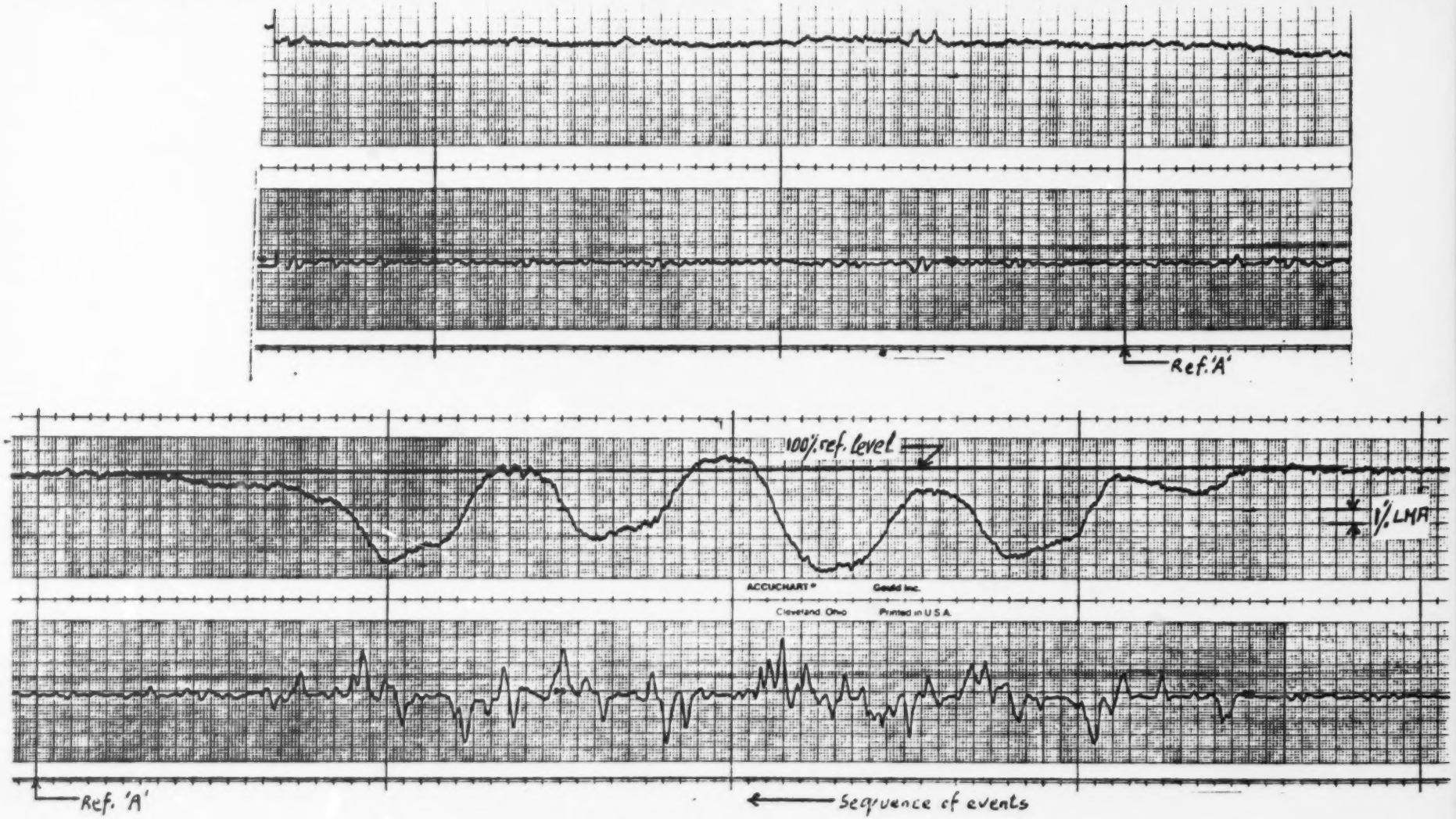


Fig. $7b_1$ — Test-rope 'A' with Magnograph, April 4, 1989

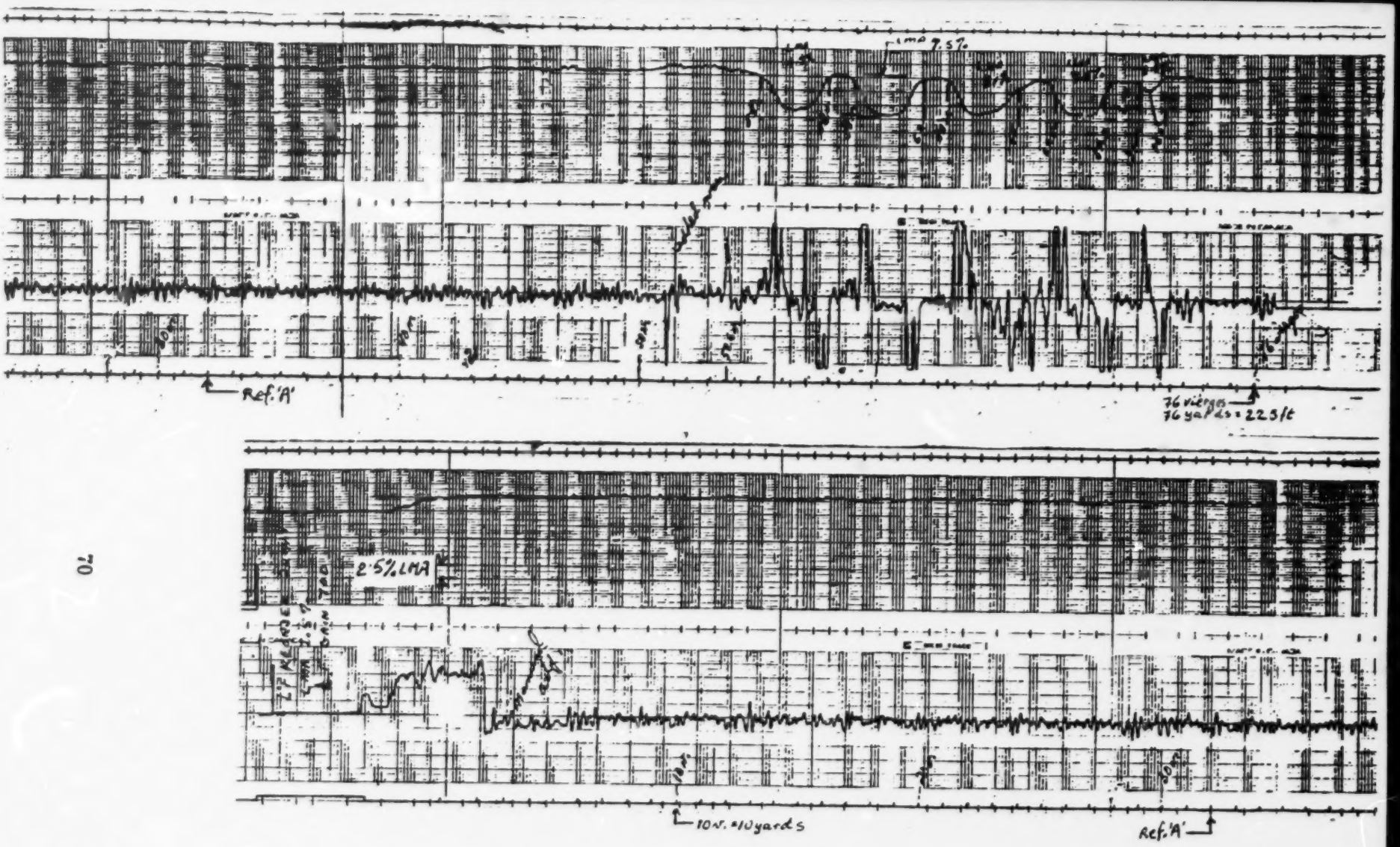


Fig. 8a — Test-rope 'B' with Magnograph, April 4, 1989

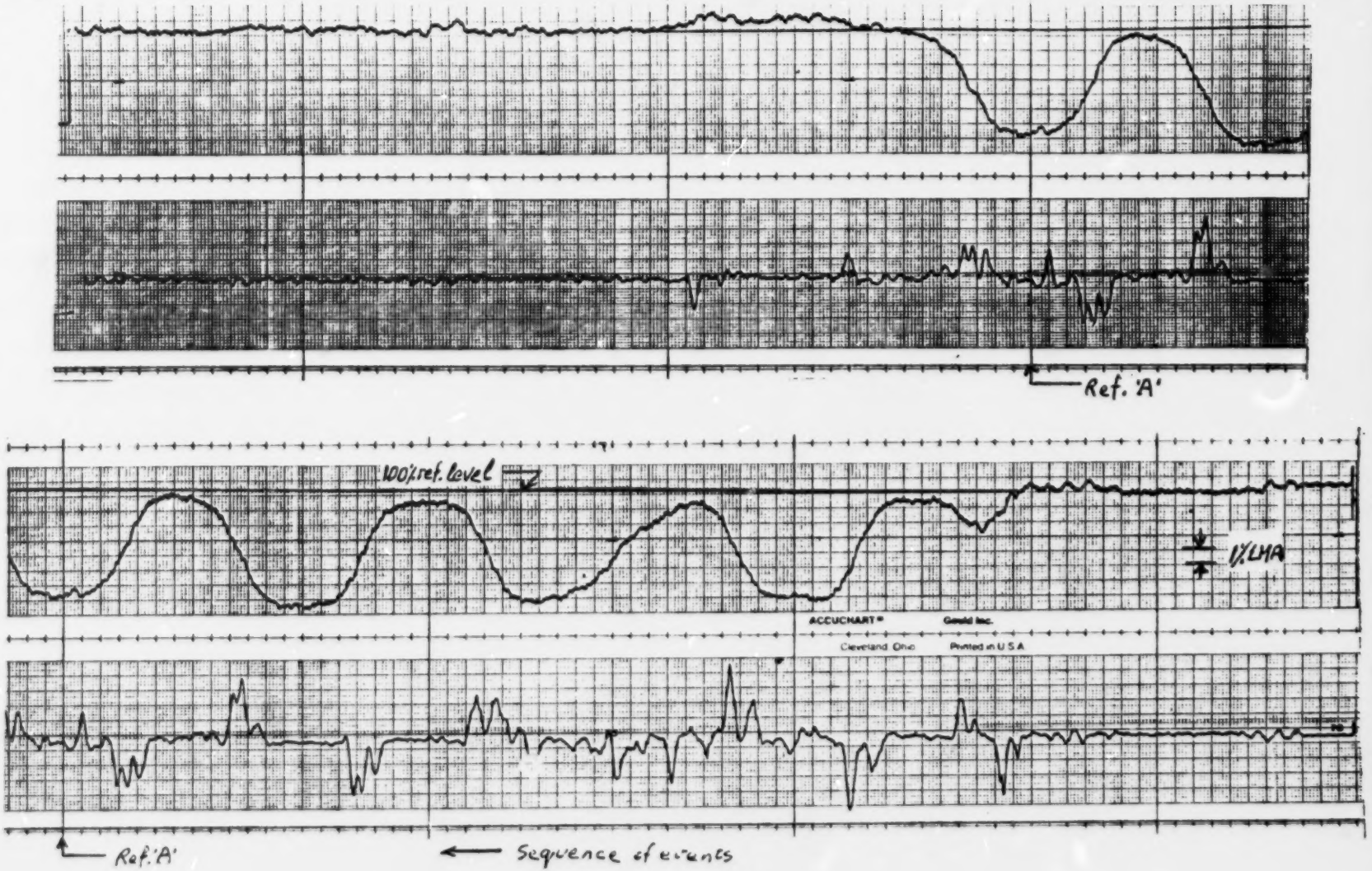


Fig. $8b_1$ — Test-rope 'B' with Magnograph, April 4, 1989

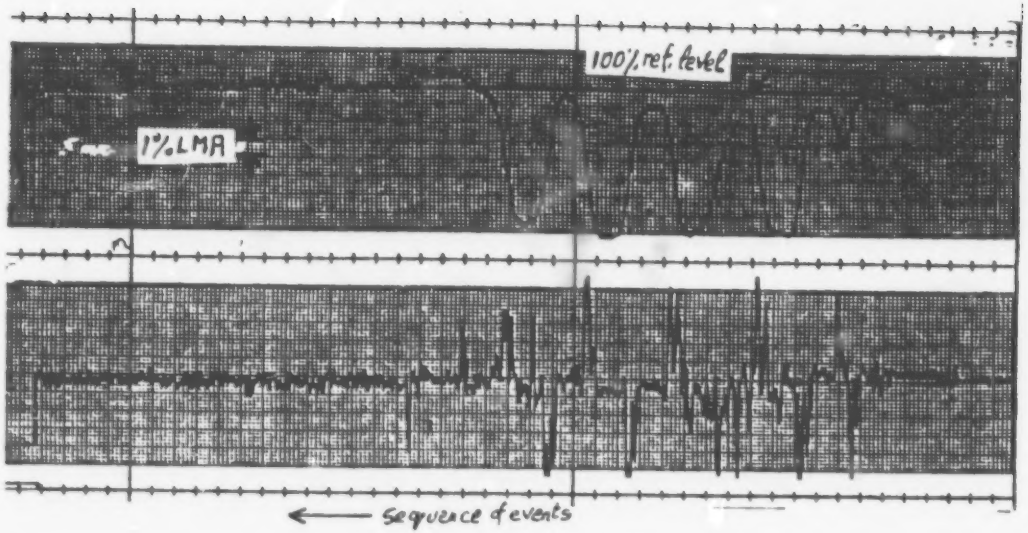


Fig. $8b_2$ — Test-rope 'B' with Magnograph, April 4, 1989

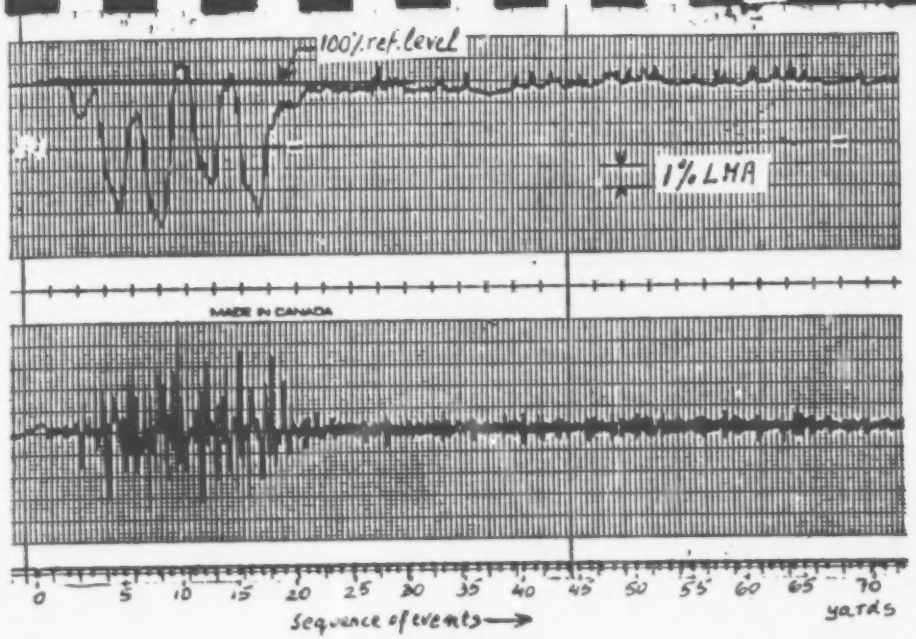


Fig. 9a — Test-rope 'A' with Magnograph, March 6, 1990

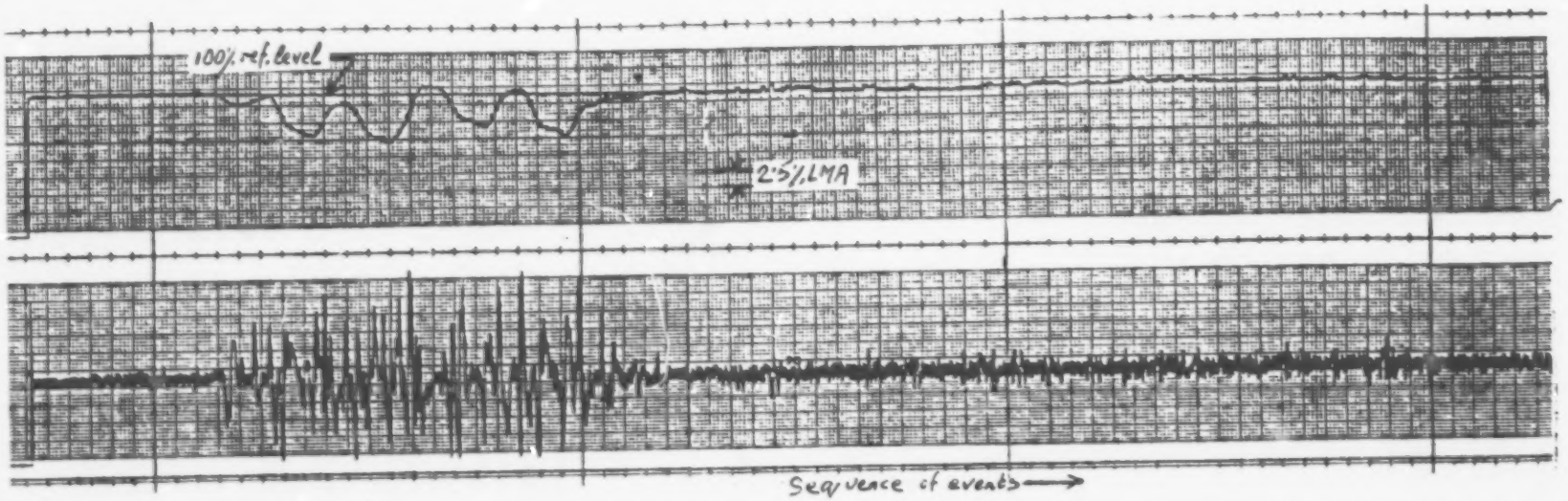


Fig. 9b — Test-rope 'A' with Magnograph, March 6, 1990

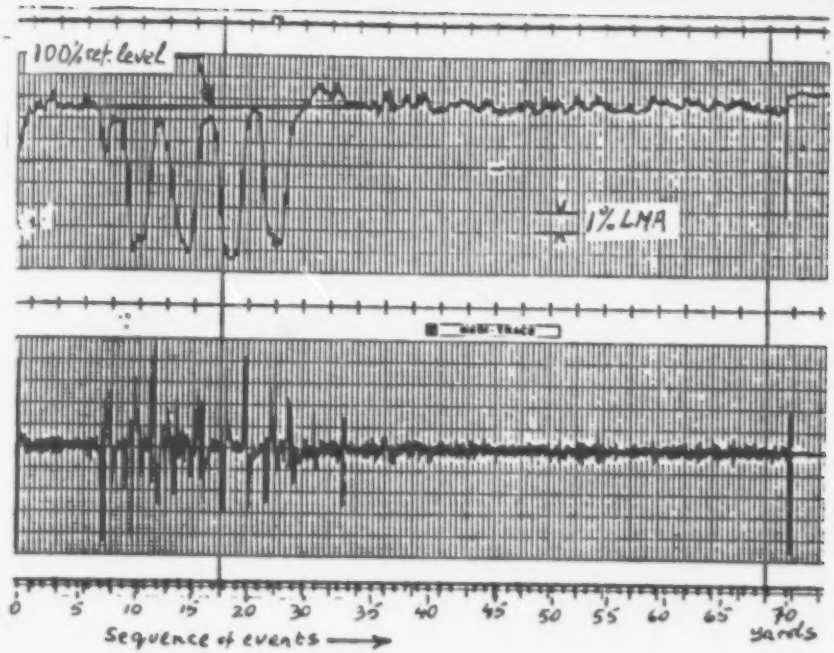


Fig. 10a — Test-rope 'B' with Magnograph, March 6, 1900

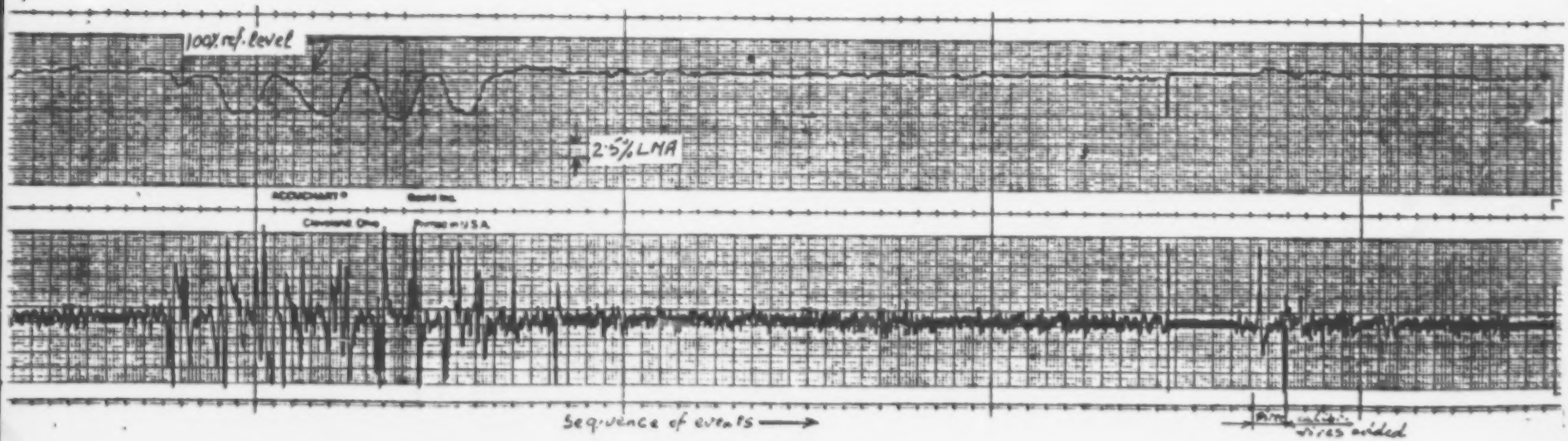


Fig. 10b — Test-rope 'B' with Magnograph, March 6, 1900

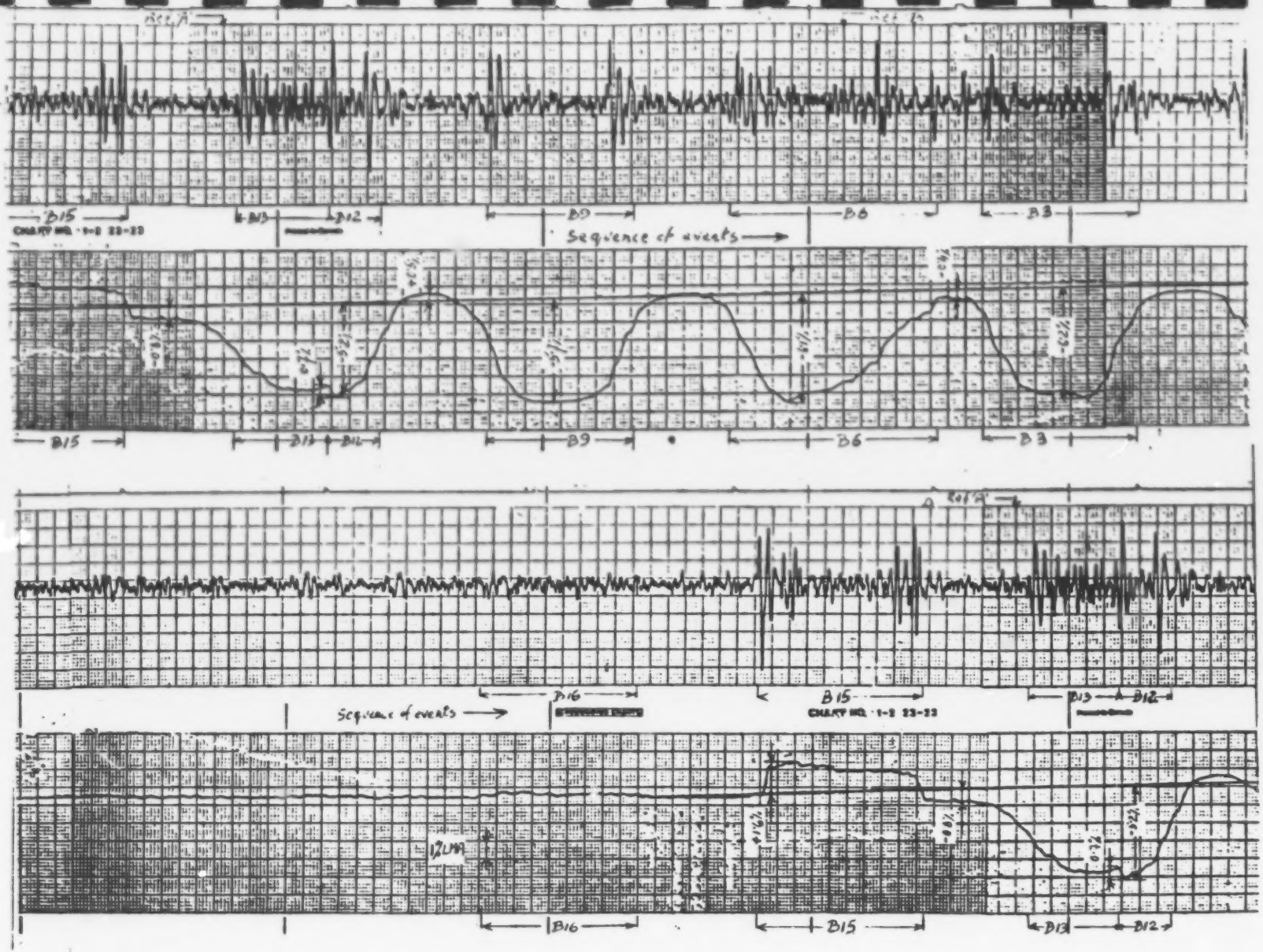


Fig. 11 — Mapping of major defects in Fig. 2a (test-rope 'B' with Rotescograph)

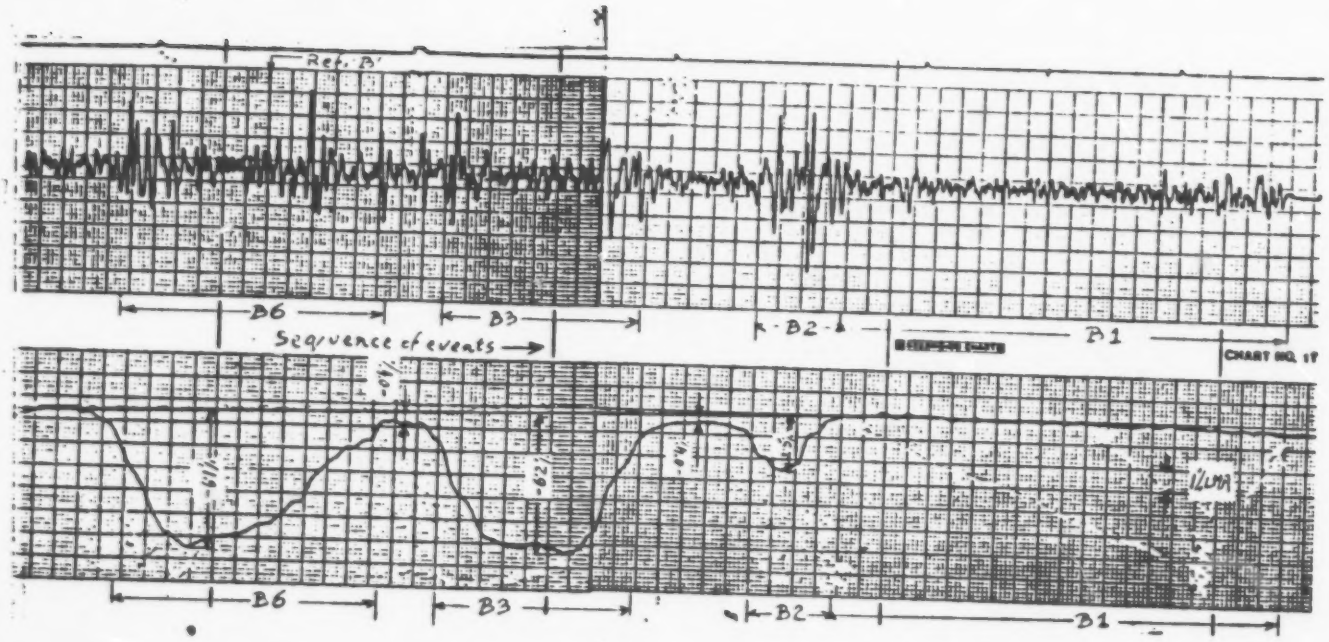


Fig. 11 (continued) — Mapping of major defects in Fig. 2a (test-rope 'B' with Rotescograph)

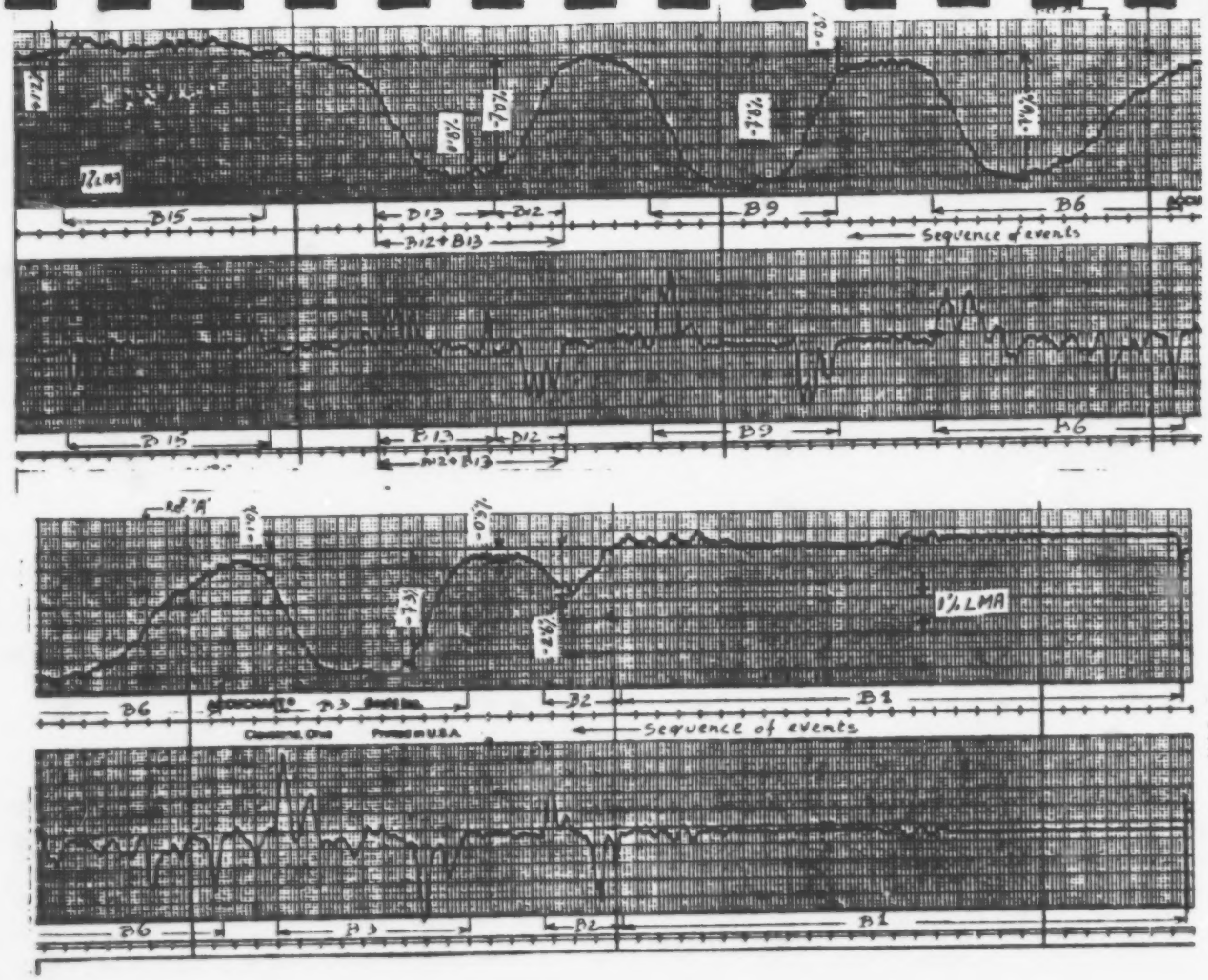


Fig. 12 — Mapping of major defects in Fig. 8b_1 (test-rope 'B' with Magnograph)

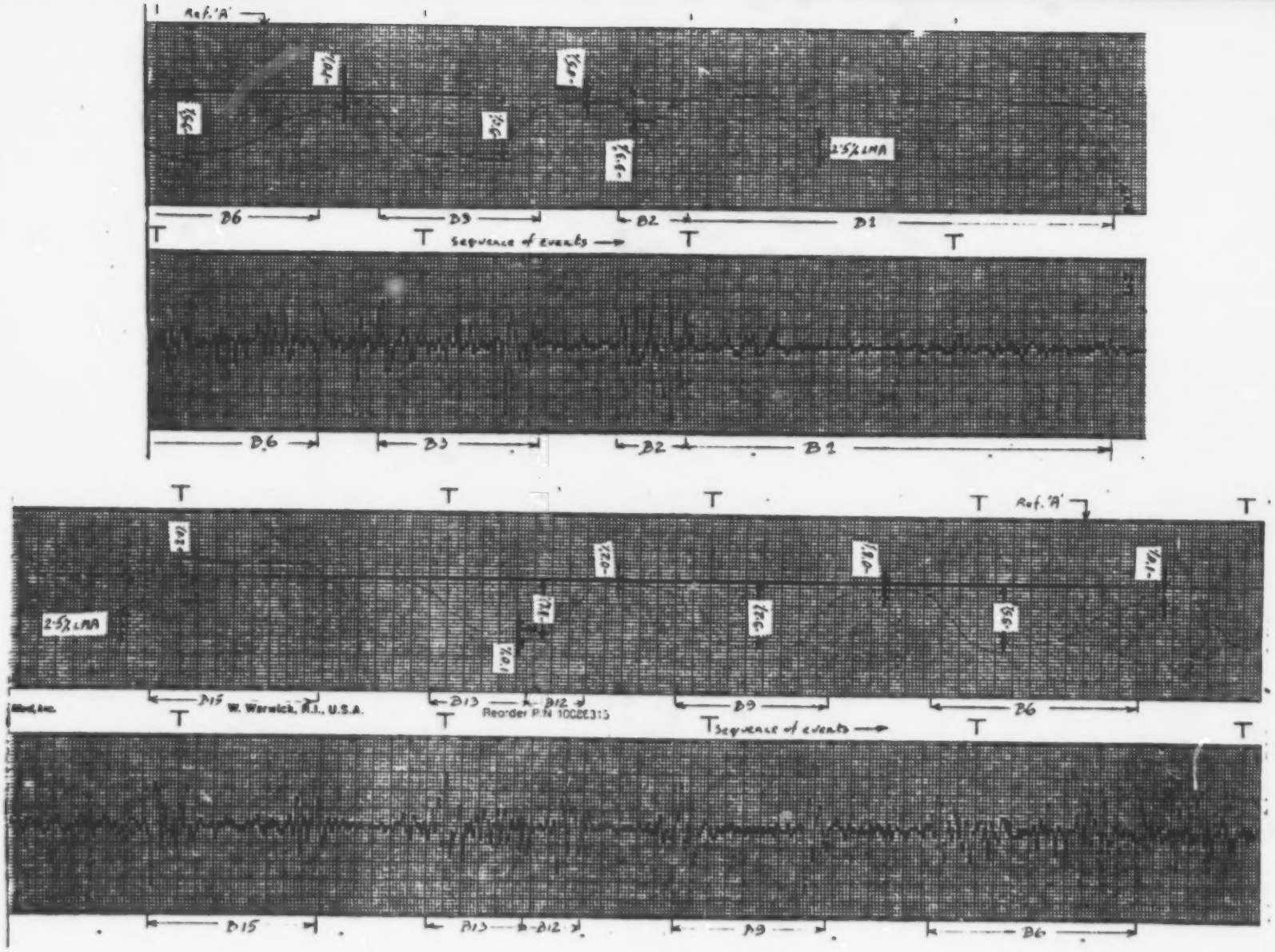


Fig. 13 — Mapping of major defects in Fig. 4a (test-rope 'B' with LMA-250)

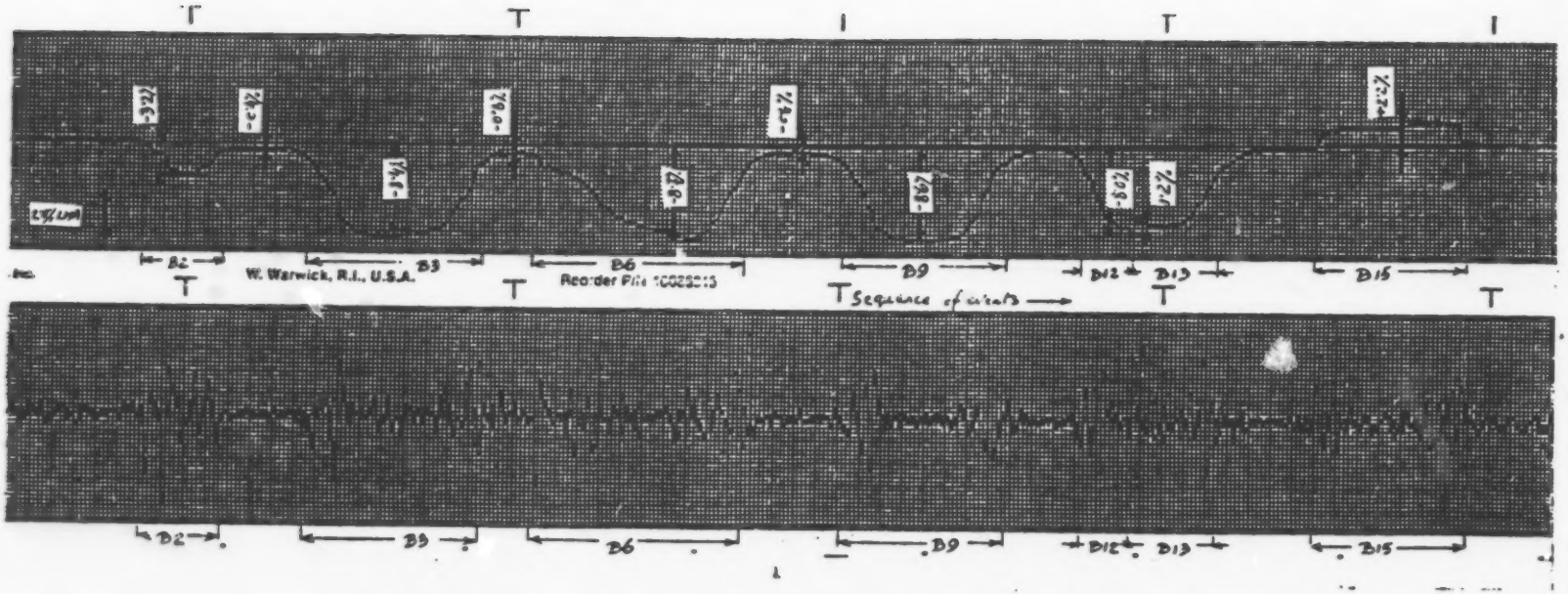


Fig. 14 — Mapping of major defects in Fig. 6 (test-rope 'B' with LMA-250)

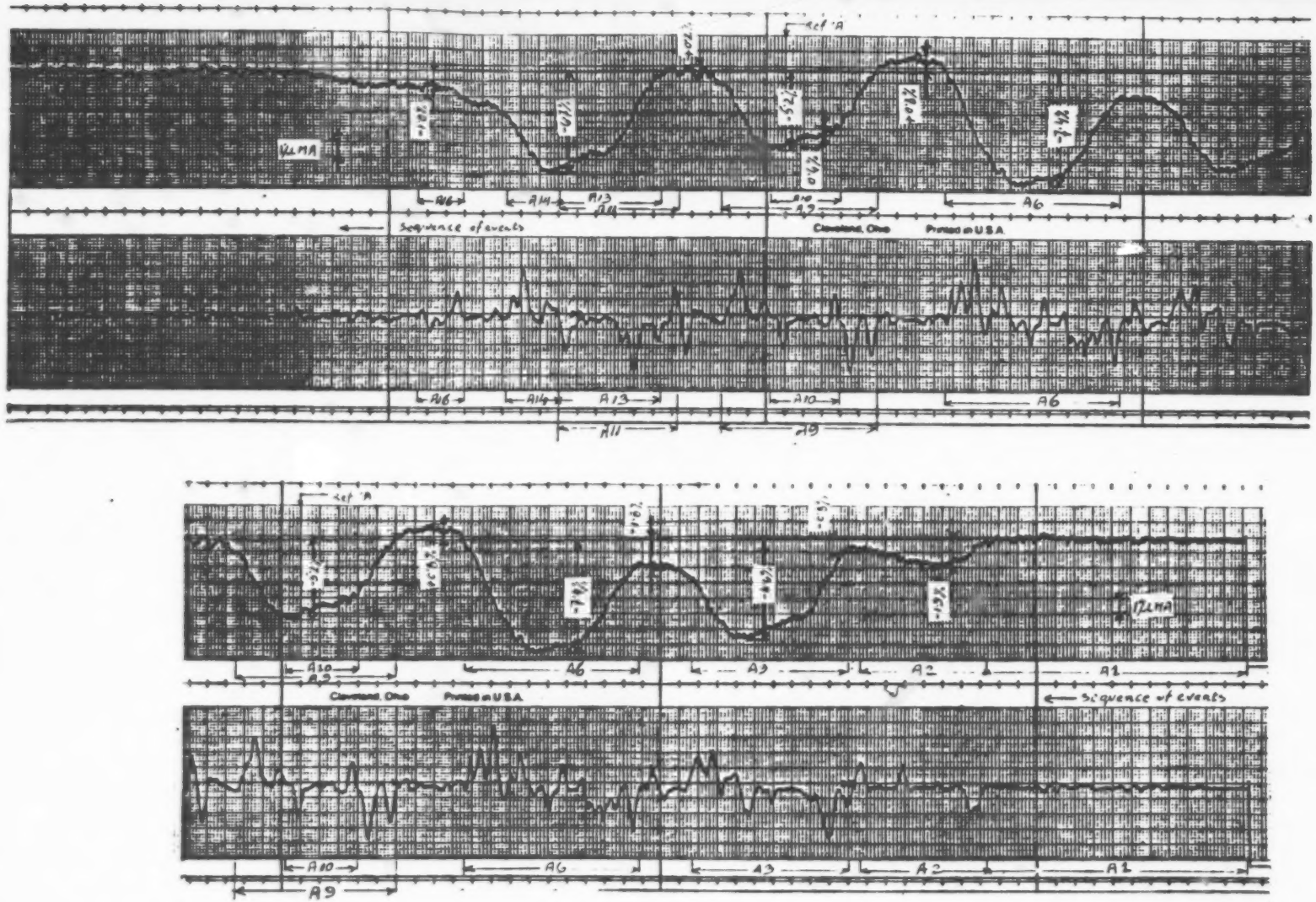


Fig. 15 — Mapping of major defects in Fig. $7b_1$ (test-rope 'A' with Magnograph)

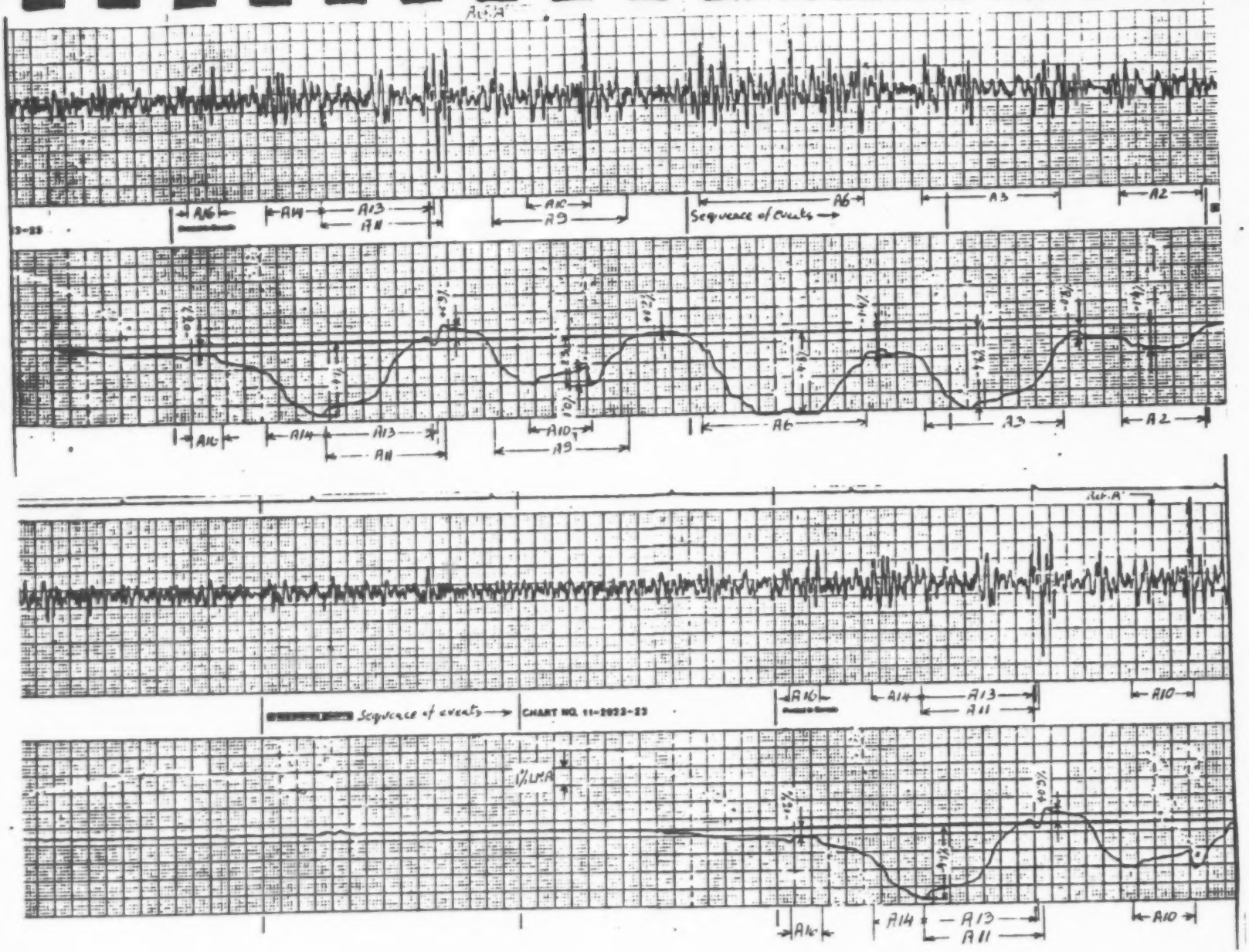


Fig. 16 — Mapping of major defects in Fig. 1a (test-rope 'A' with Rotescograph)

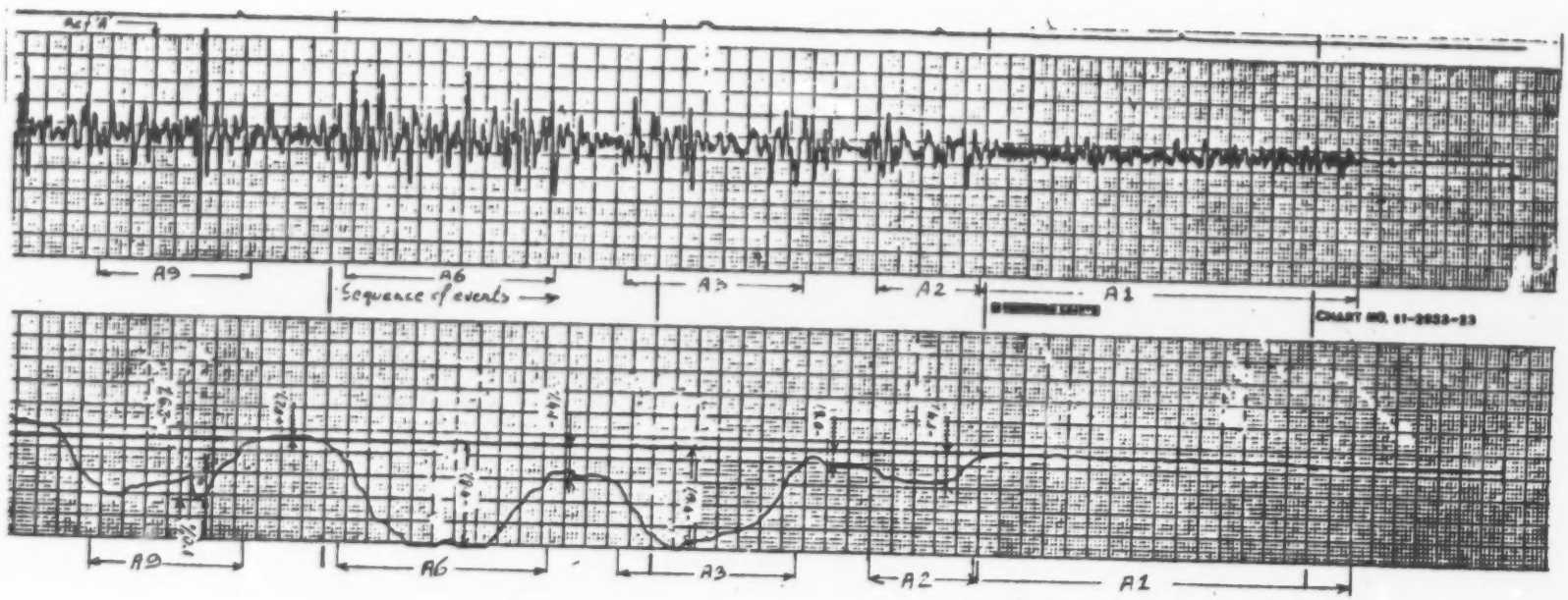


Fig. 16 (continued) — Mapping of major defects in Fig. 1a (test-rope 'A' with Rotescograph)

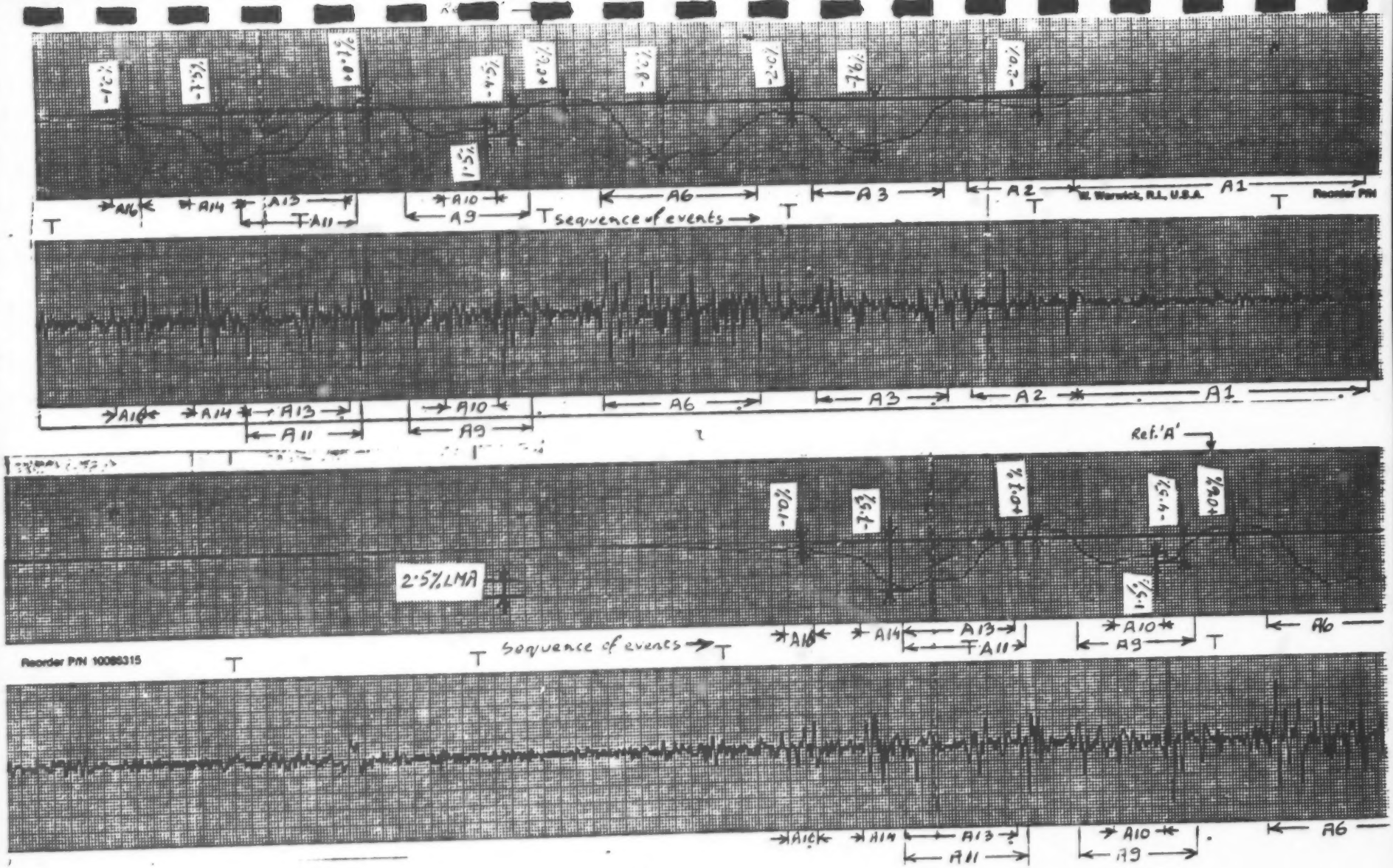


Fig. 17 — Mapping of major defects in Fig. 3 (test-rope 'A' with LMA-250)

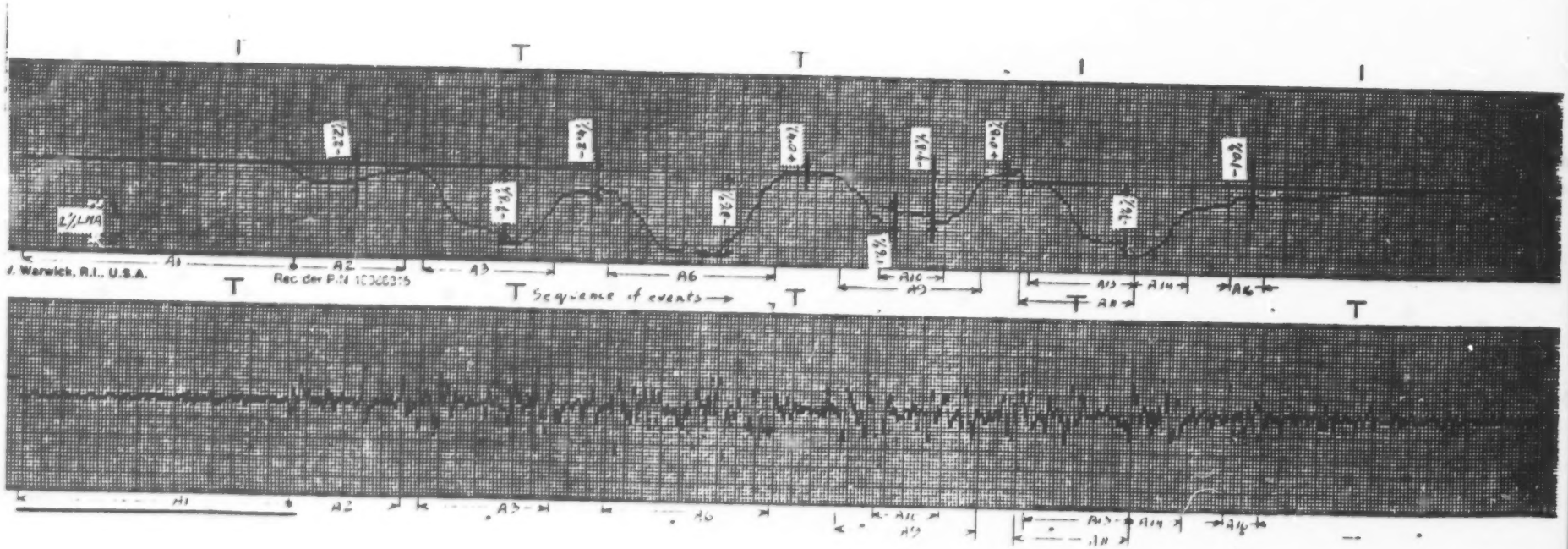


Fig. 18 — Mapping of major defects in Fig. 5 (test-rope 'A' with LMA-250)

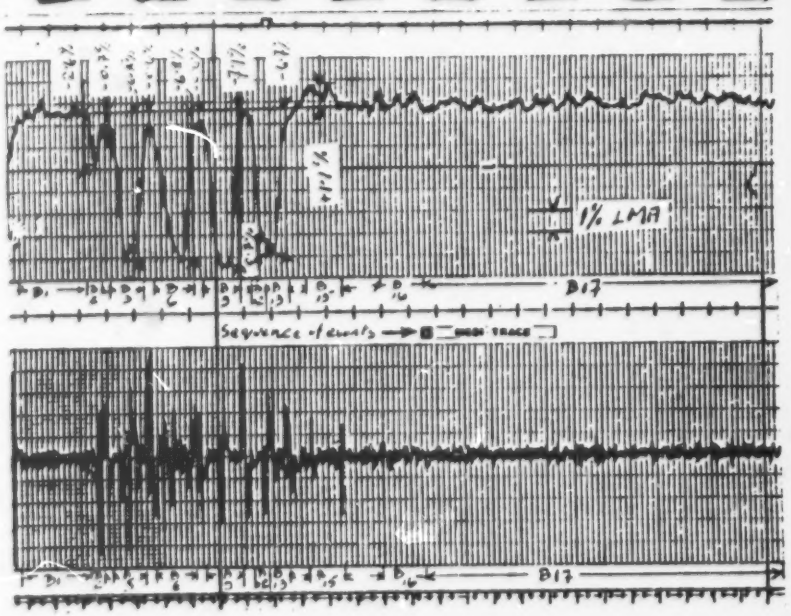


Fig. 10a — Mapping of major defects in Fig. 10a (test-rope 'B' with Magnograph)

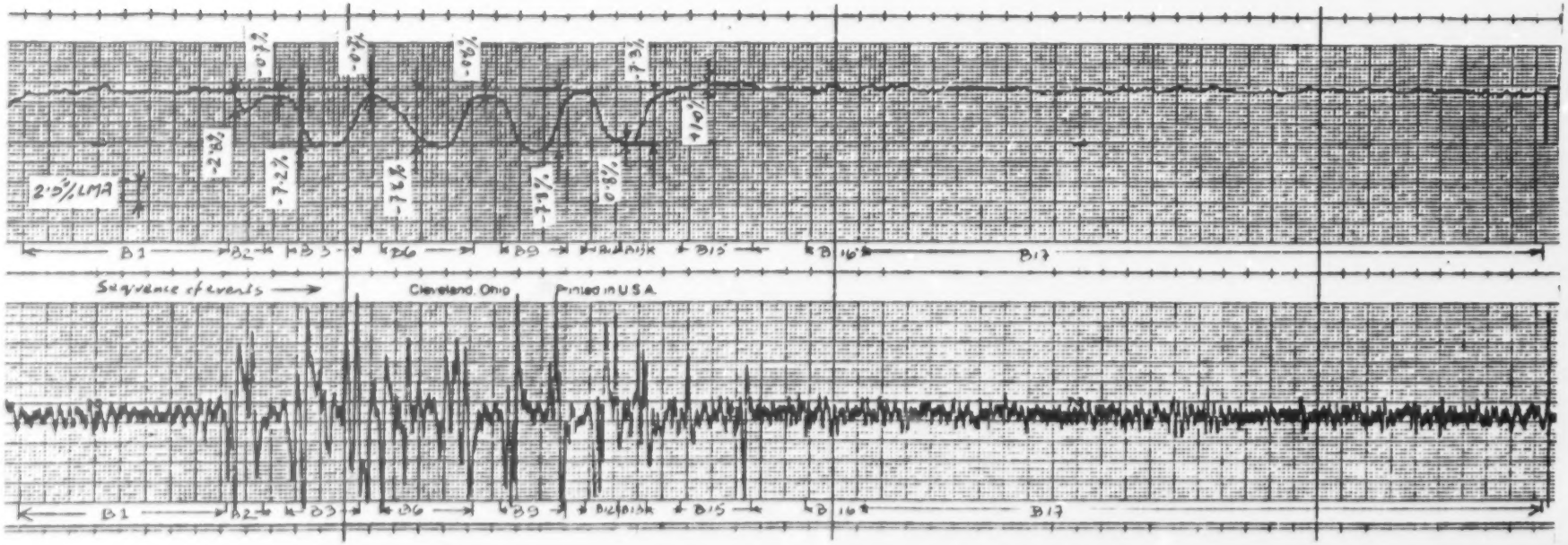


Fig. 10b — Mapping of major defects in Fig. 10b (test-rope 'B' with Magnograph)

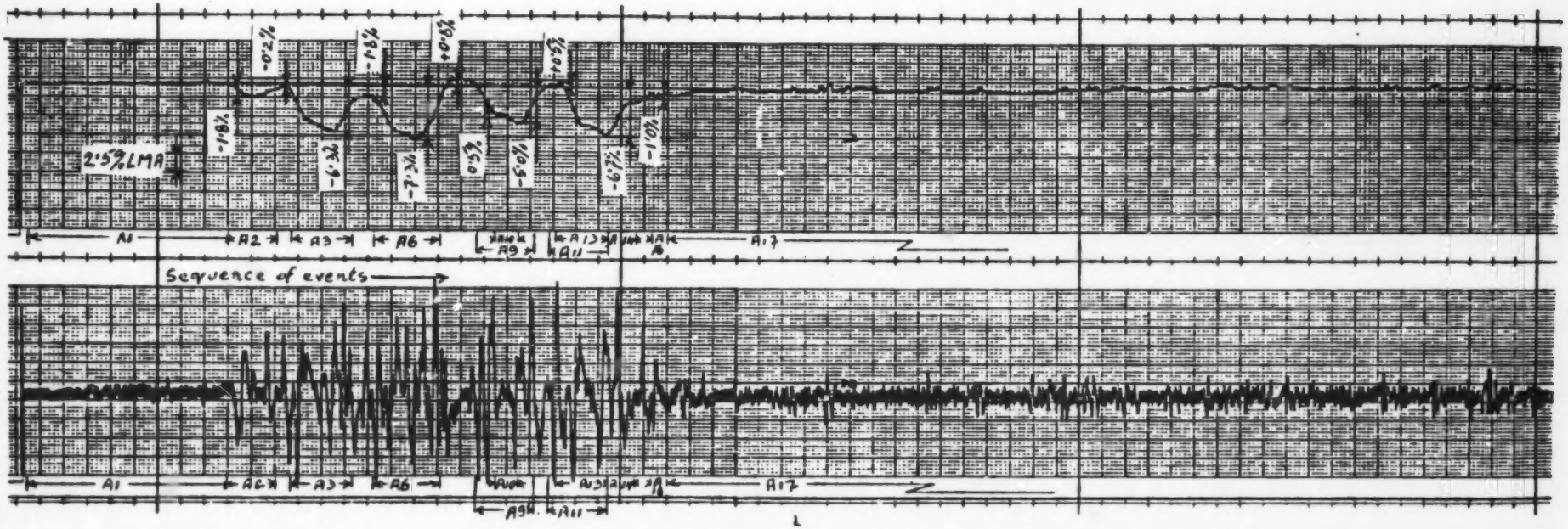


Fig. 20 — Mapping of major defects in Fig. 9b (test-rope 'A' with Magnograph)

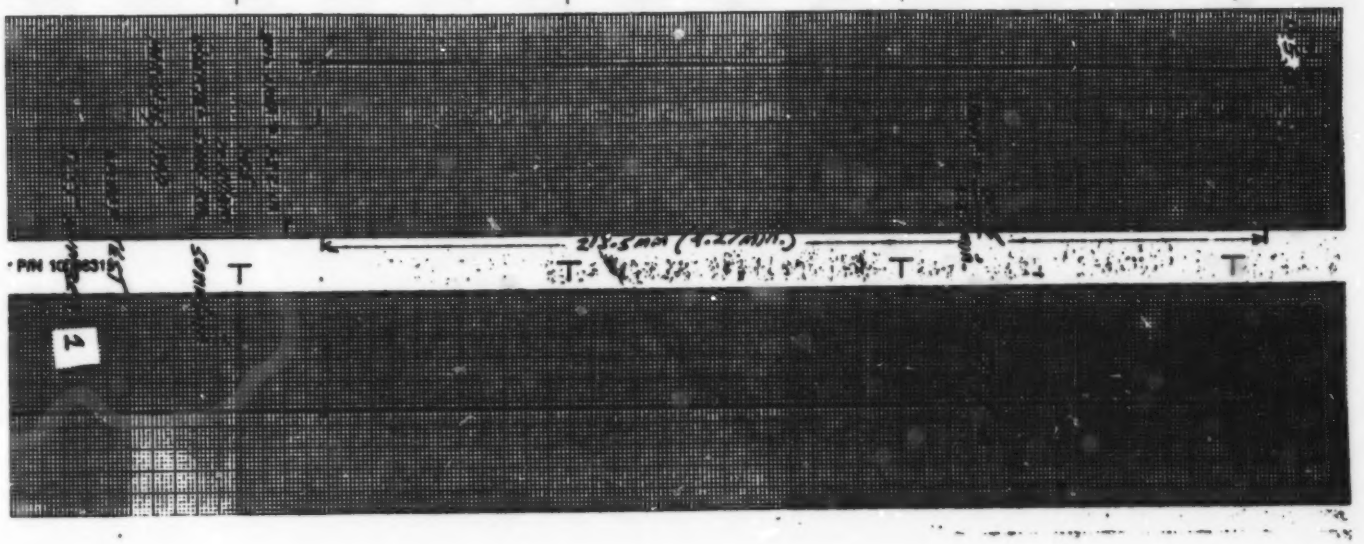


Fig. 21a — Droop test #1 of LMA-250 instrument, March, 1990

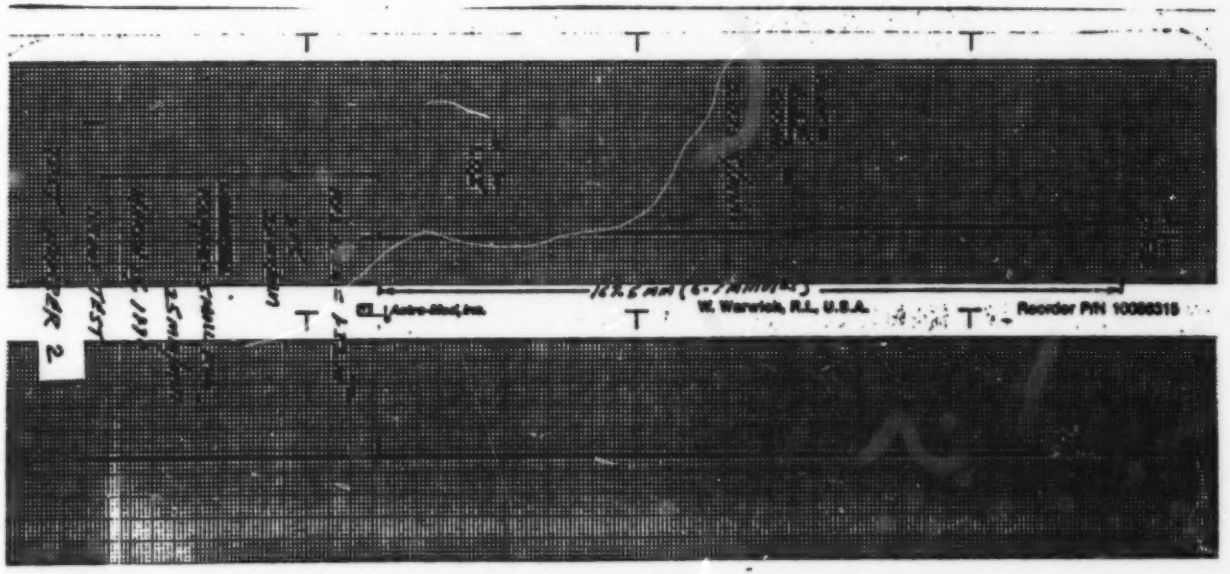


Fig. 21b — Droop test #2 of LMA-250 instrument, March, 1990

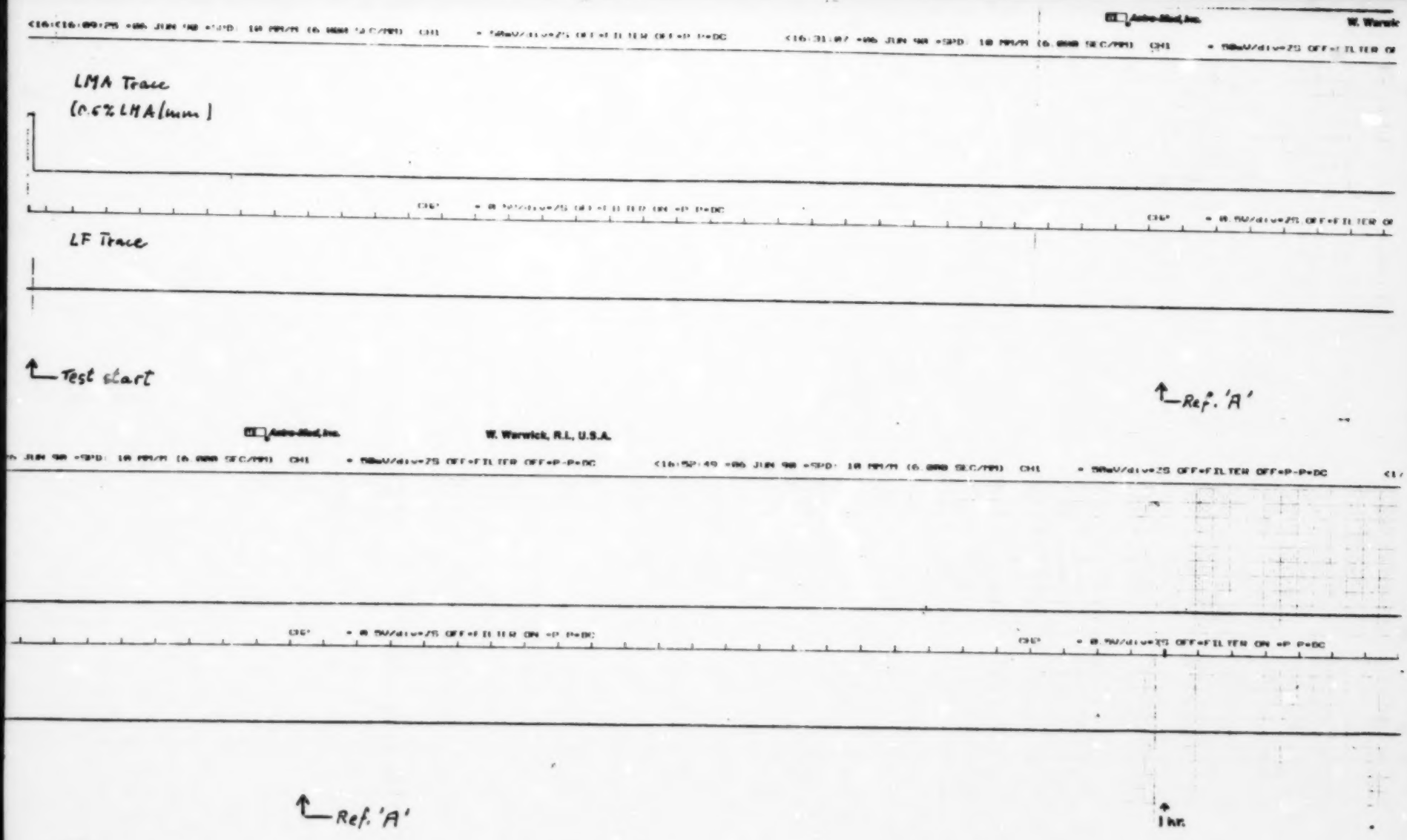


Fig. 21c — Droop test #3 of LMA-250 instrument, June, 1990. Result: 0.5% LMA/hr

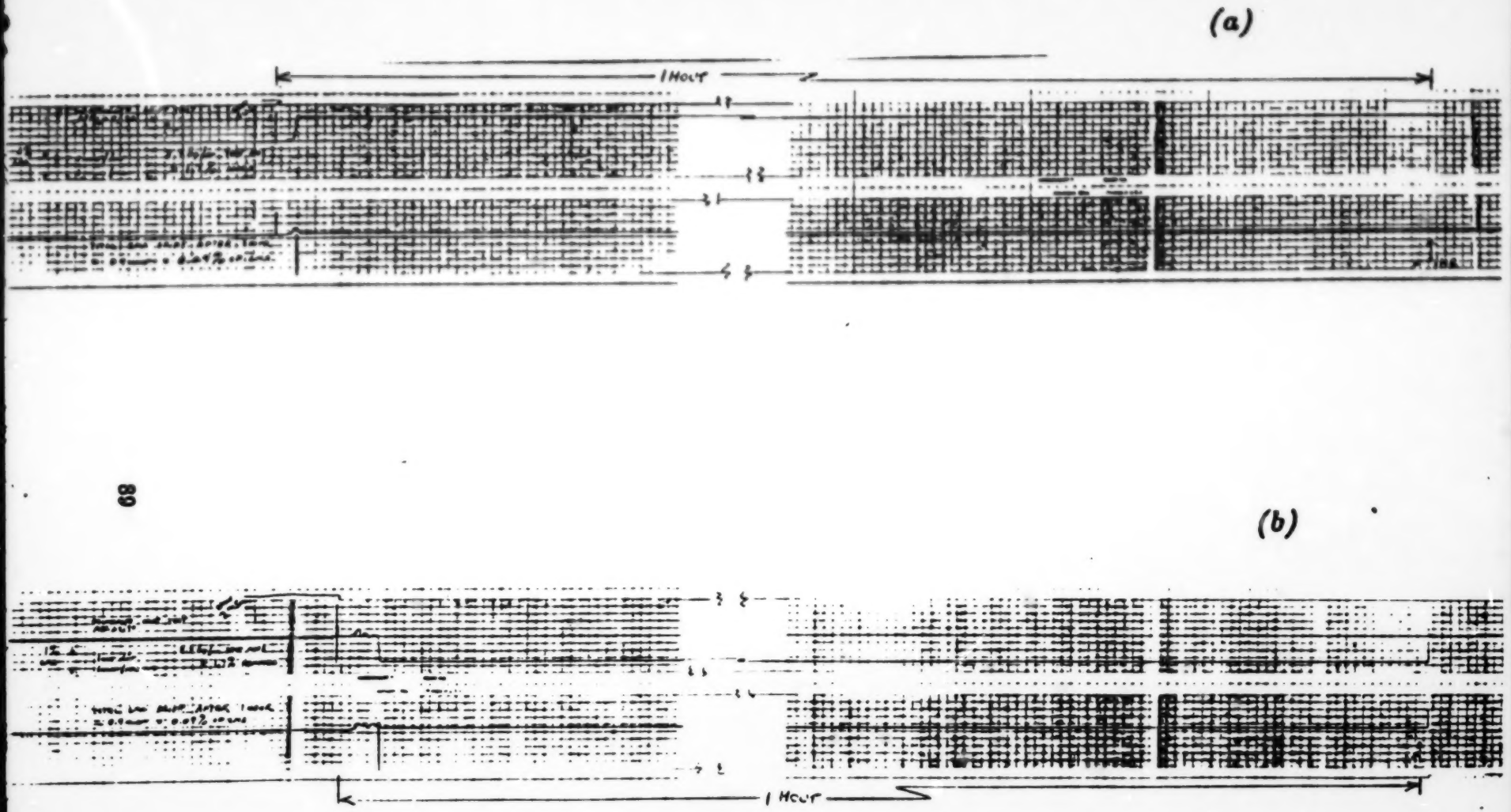


Fig. 22 — Droop test of Magnograph, April, 1990, with 8.3 kg/m test-rod (approx. 1.7% of A): (a) added, (b) removed.

Result: 0.09% LMA/hr in each case

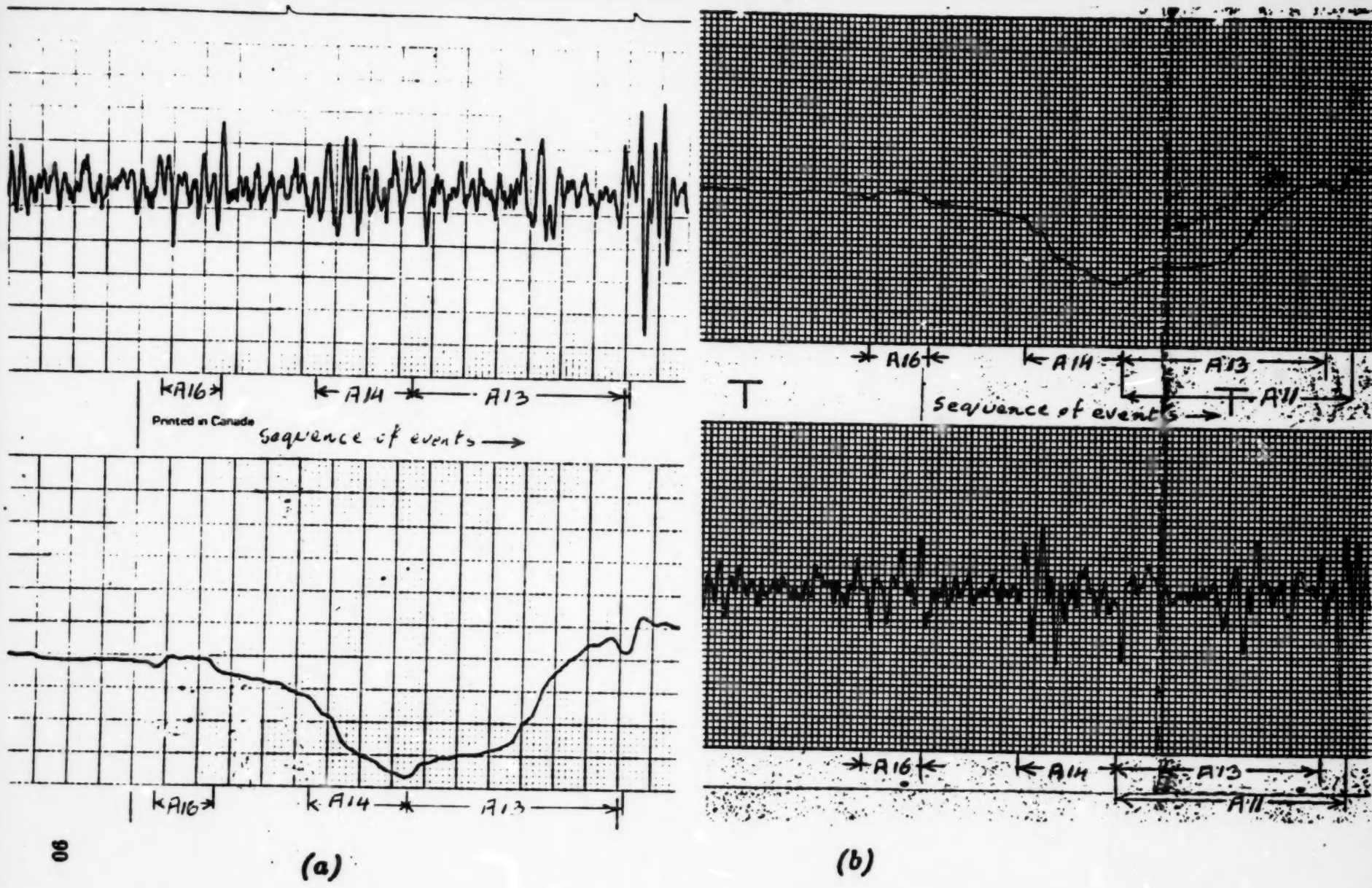
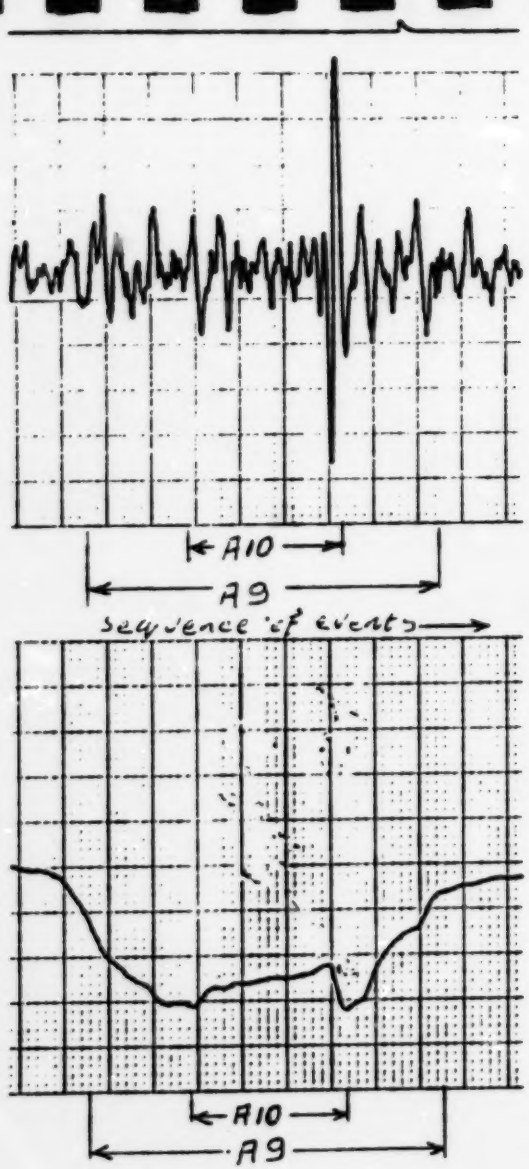
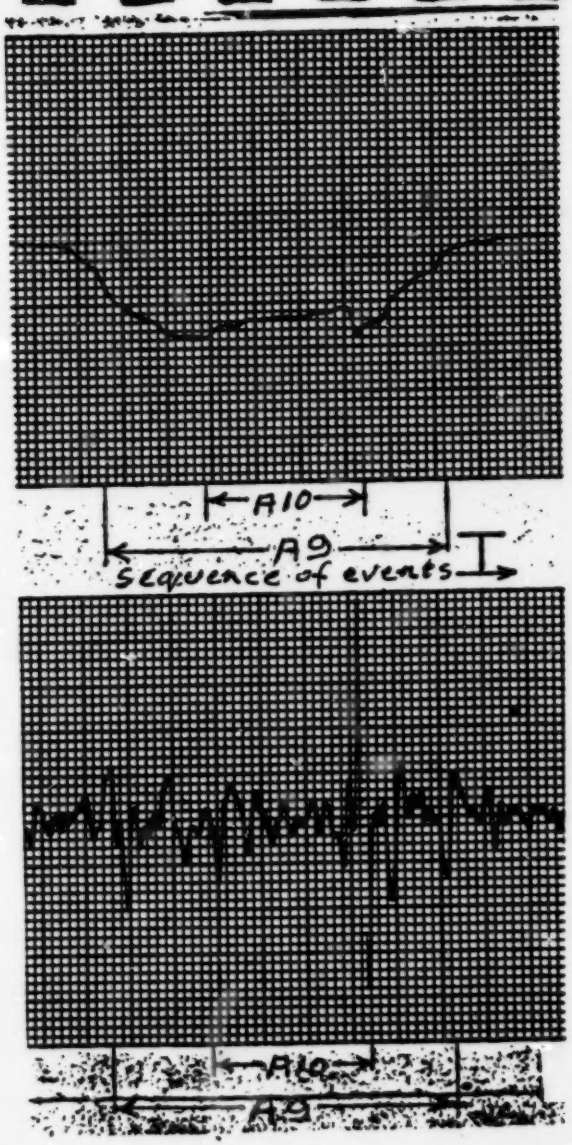


Fig. 23a — Rope 'A', April, 1989, testing with (a) Rotescograph and (b) LMA-250; defects A16, A14 and A13



(a)



(b)

Fig. 23b — Rope 'A', April, 1989, testing with (a) Rotescograph and (b) LMA-250; defects A10 and A9

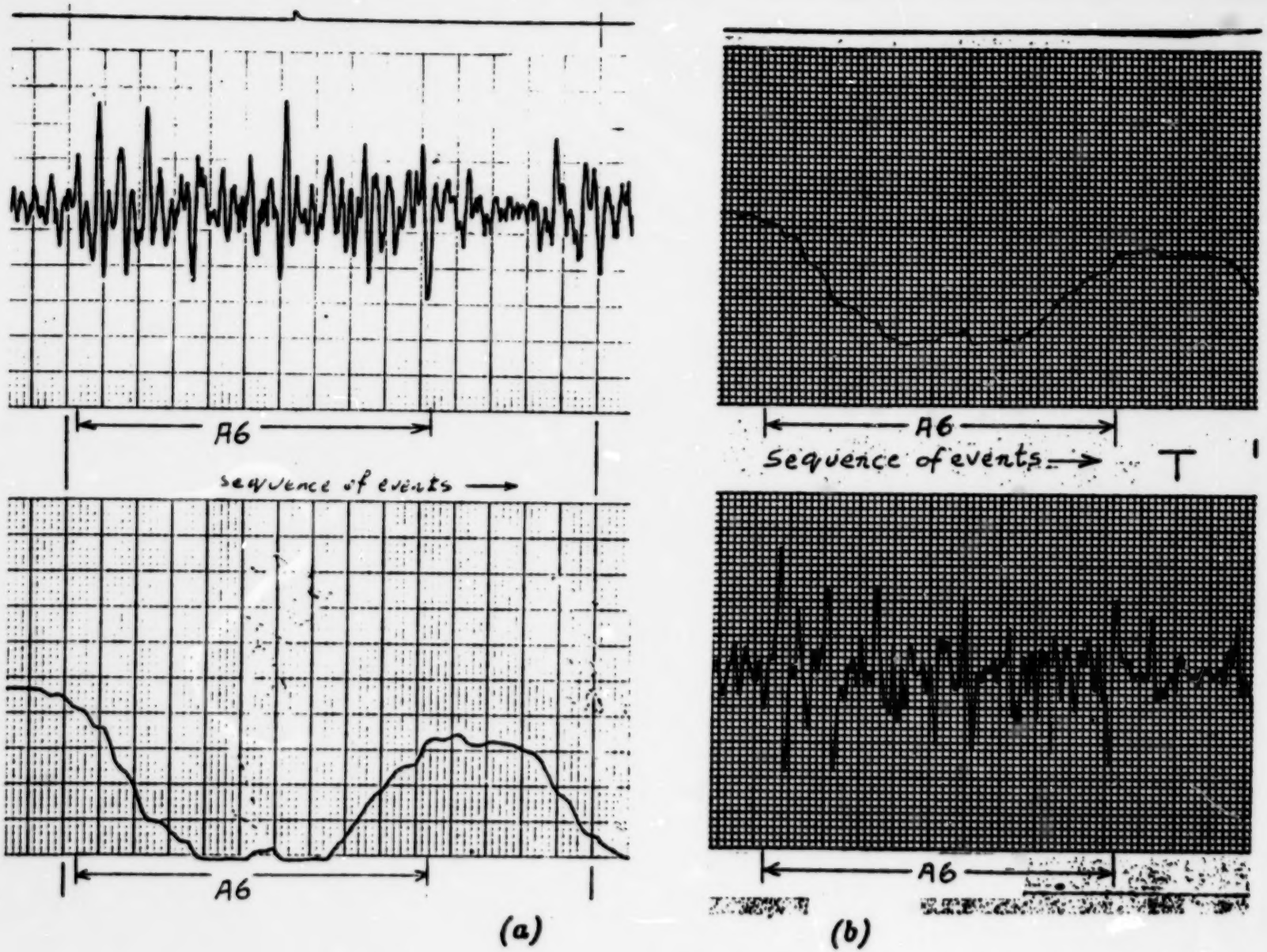


Fig. 23c — Rope 'A', April, 1989, testing with (a) Rotescograph and (b) LMA-250; defect A6

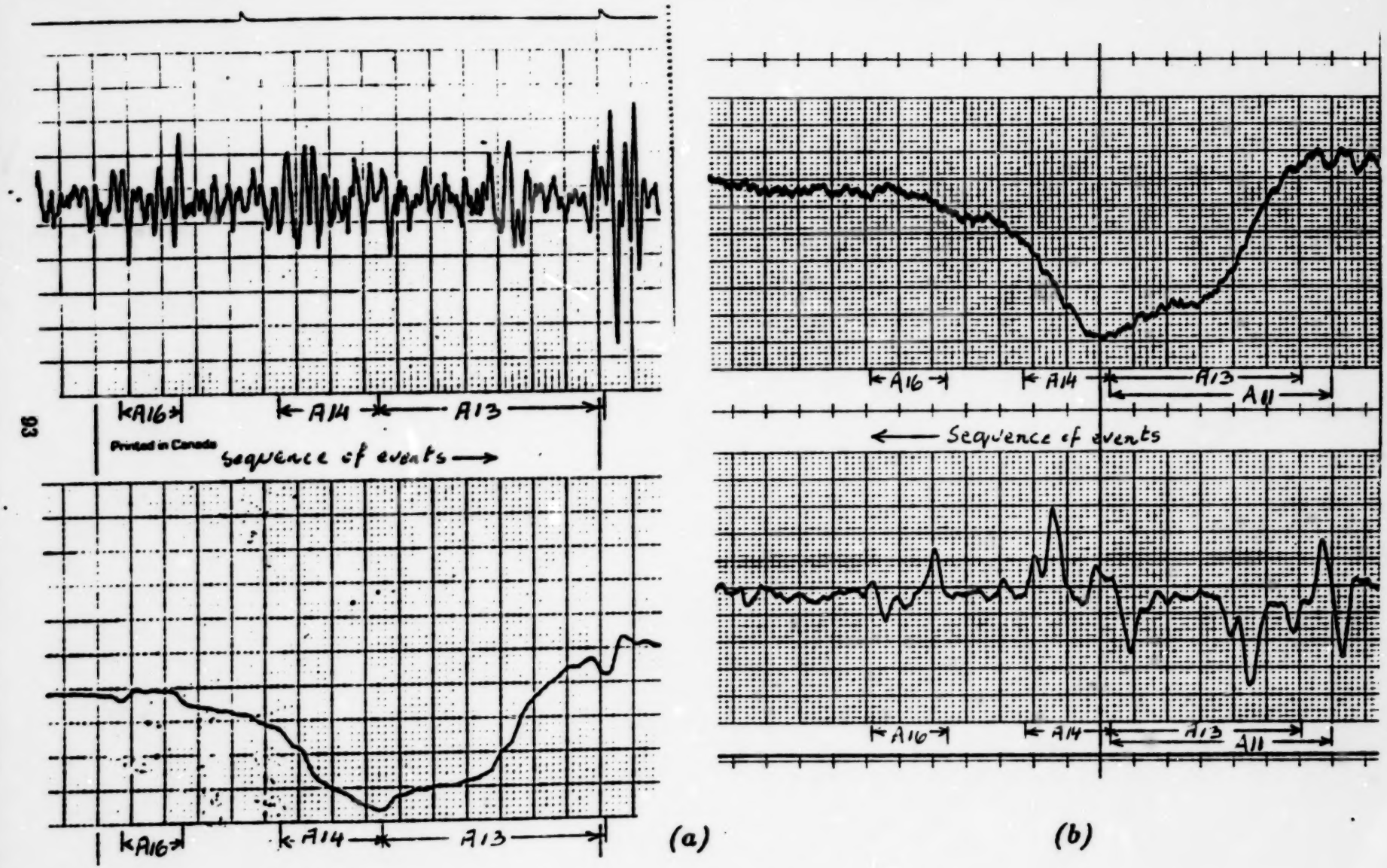
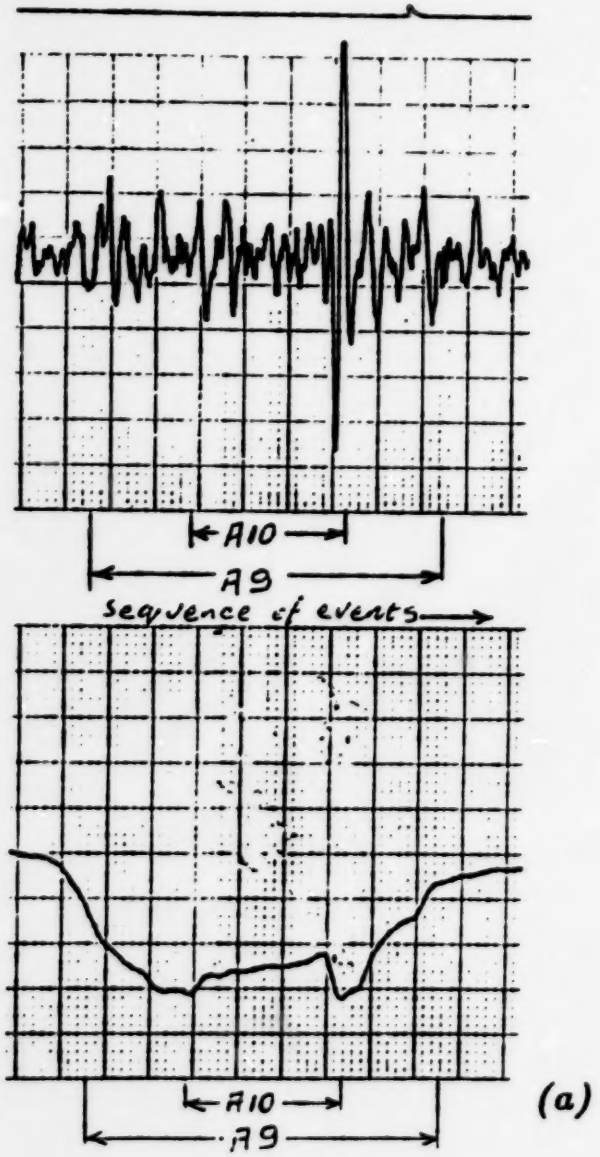


Fig. 24a — Rope 'A', April, 1989, testing with (a) Rotescograph and (b) Magnograph; defects A16, A14 and A13



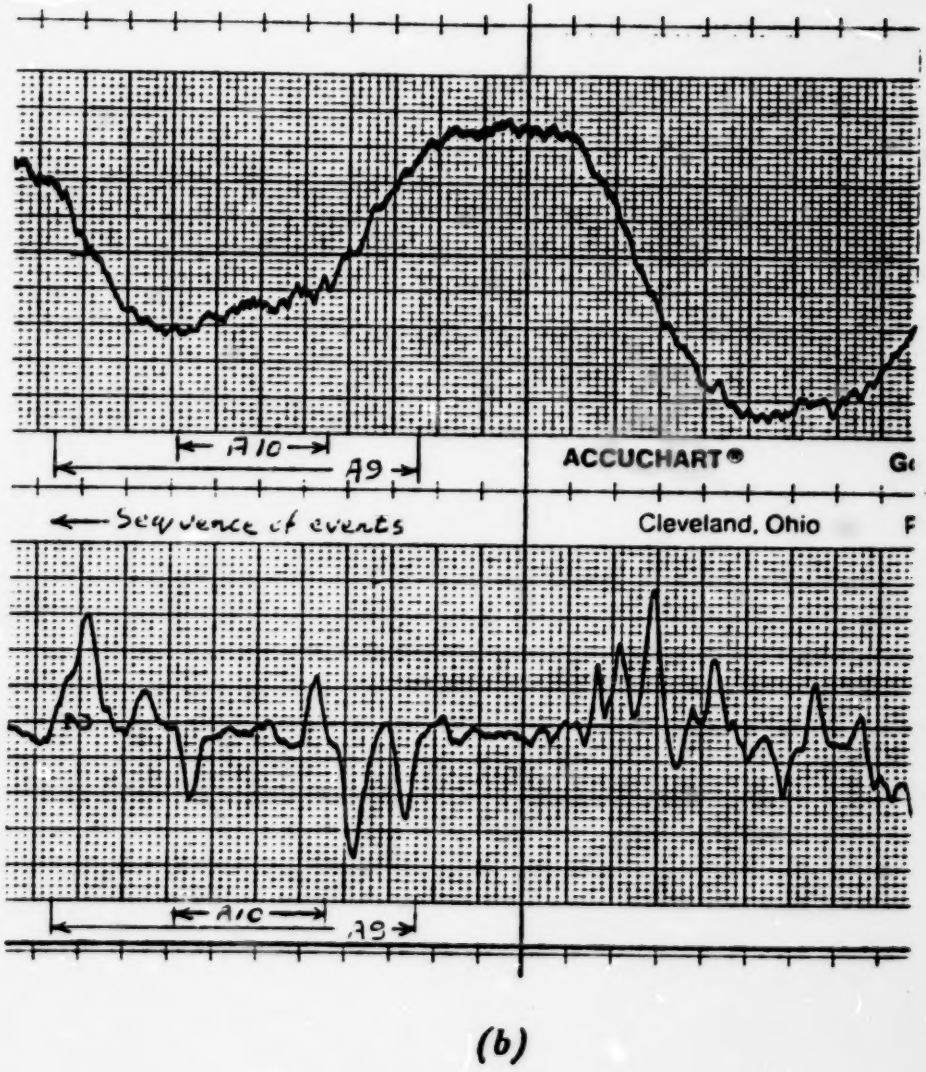


Fig. 24b — Rope 'A', April, 1989, testing with (a) Rotescograph and (b) Magnograph; defects A10 and A9

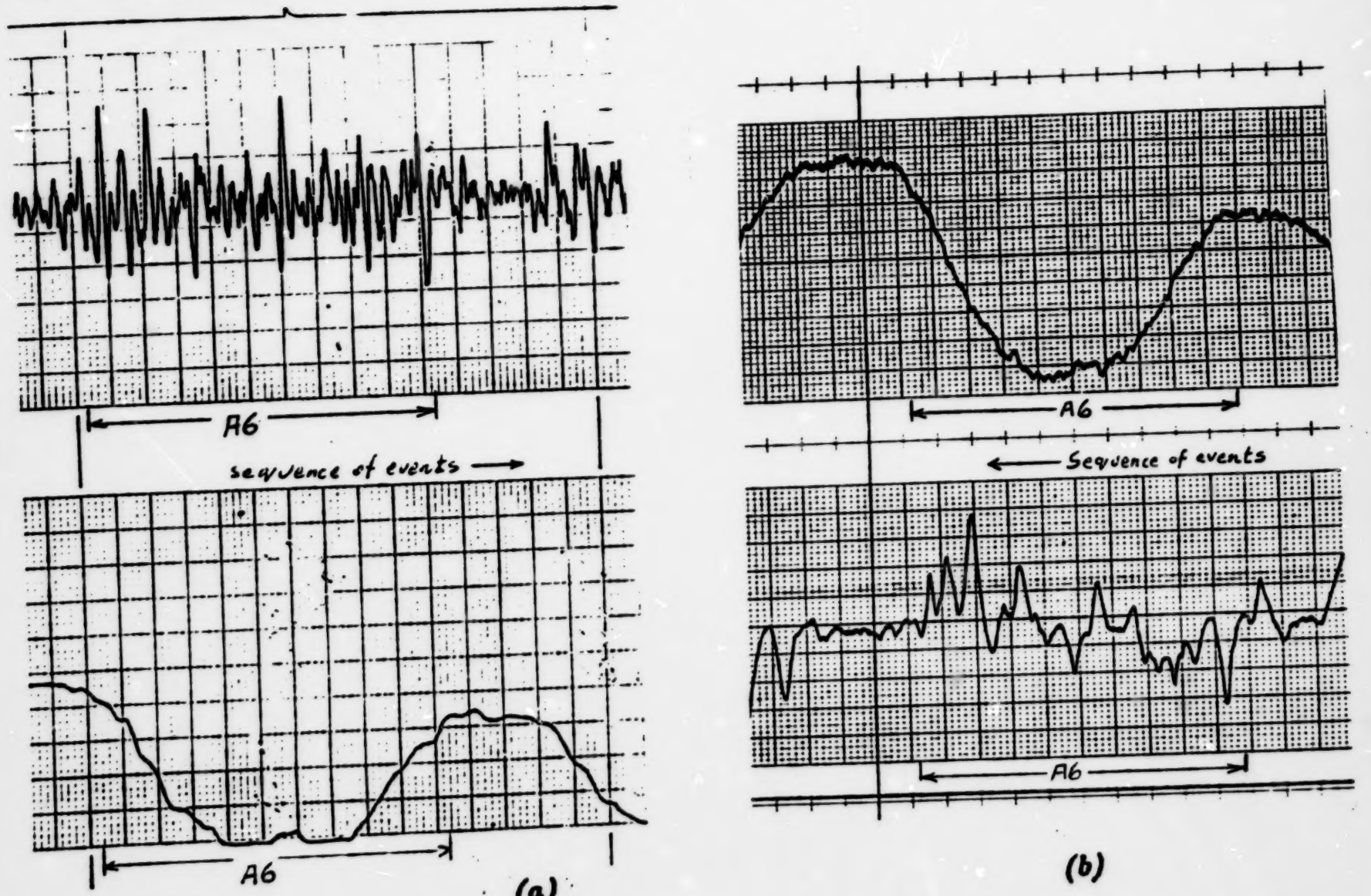


Fig. 24c — Rope 'A', April, 1989, testing with (a) Rotescograph and (b) Magnograph; defect A6

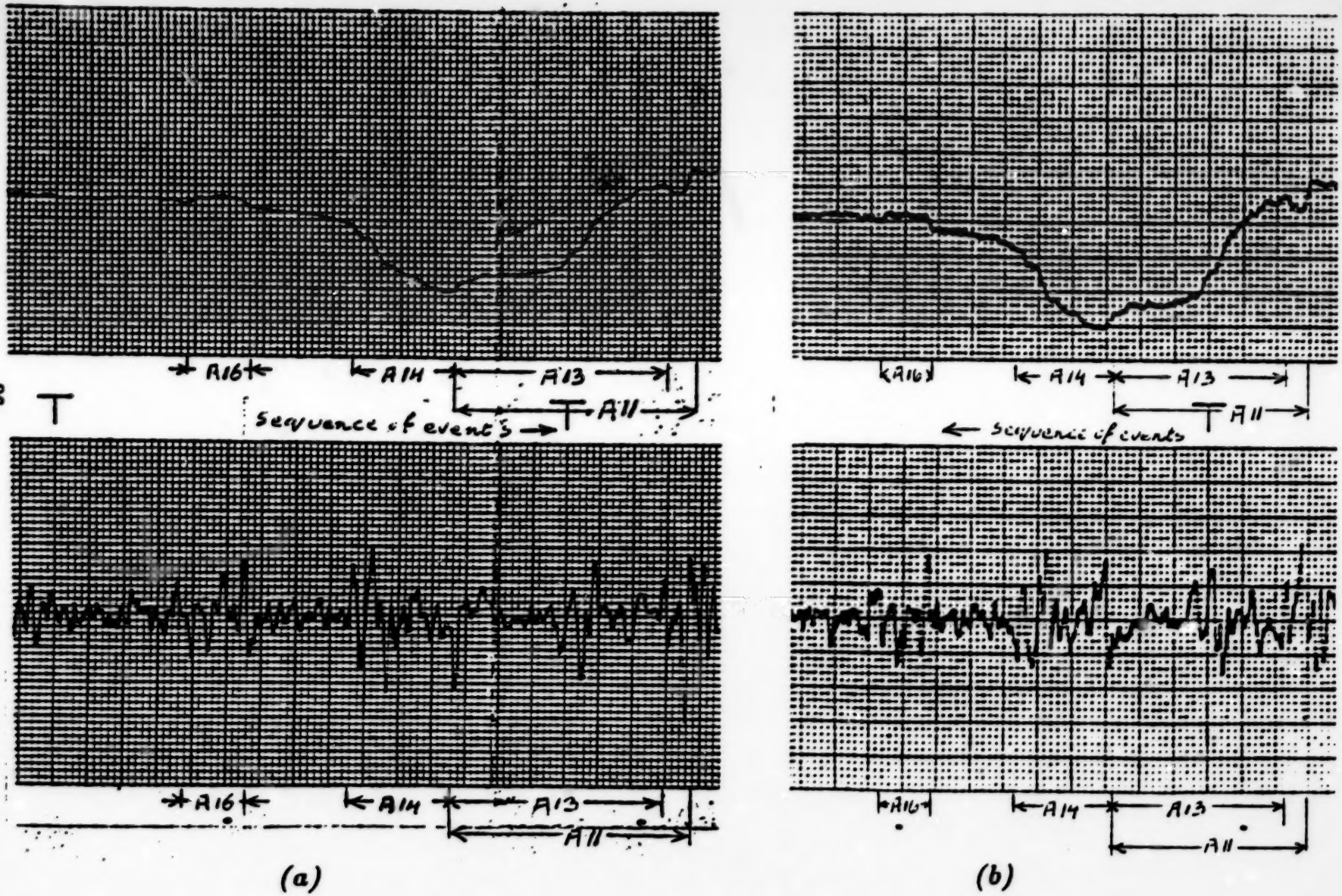


Fig. 25a — Rope 'A', (a) April, 1989, and (b) March, 1990, testing with LMA-250; defects A16, A14 and A13

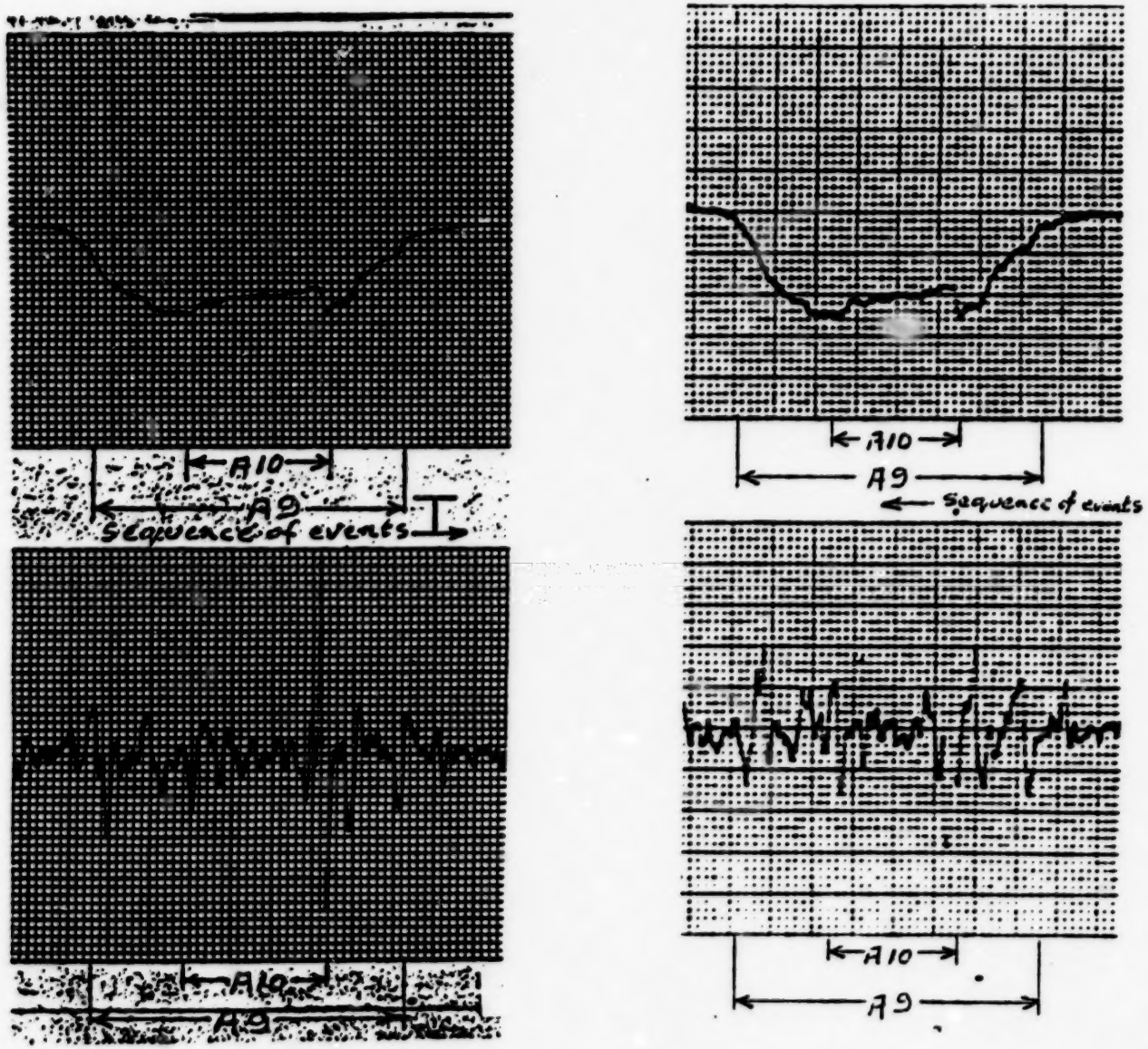


Fig. 25b — Rope 'A', (a) April, 1989, and (b) March 1990, testing with LMA-250; defects A10 and A9

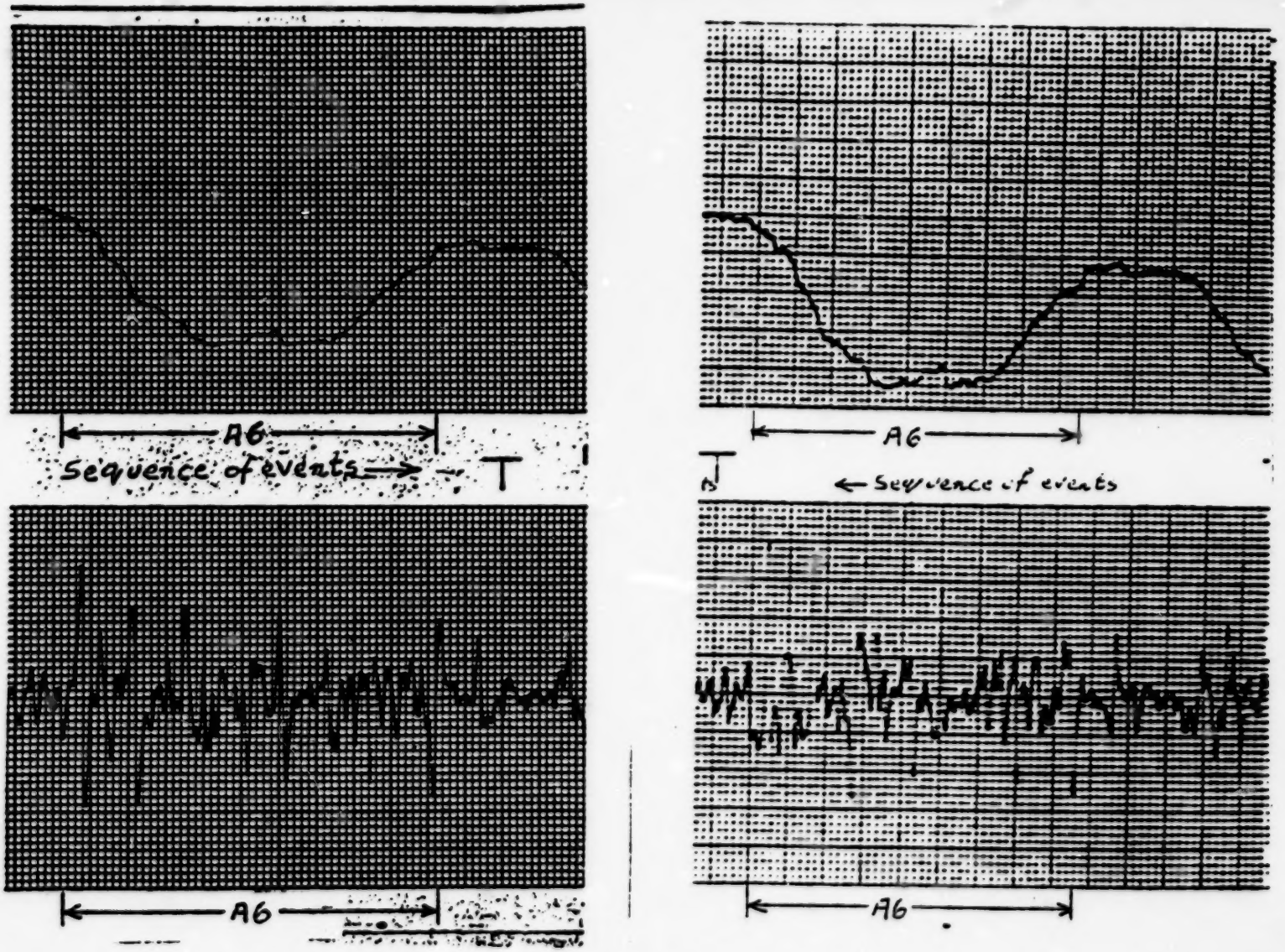


Fig. 25c — Rope 'A', (a) April, 1989, and (b) March 1990, testing with LMA-250; defect A6

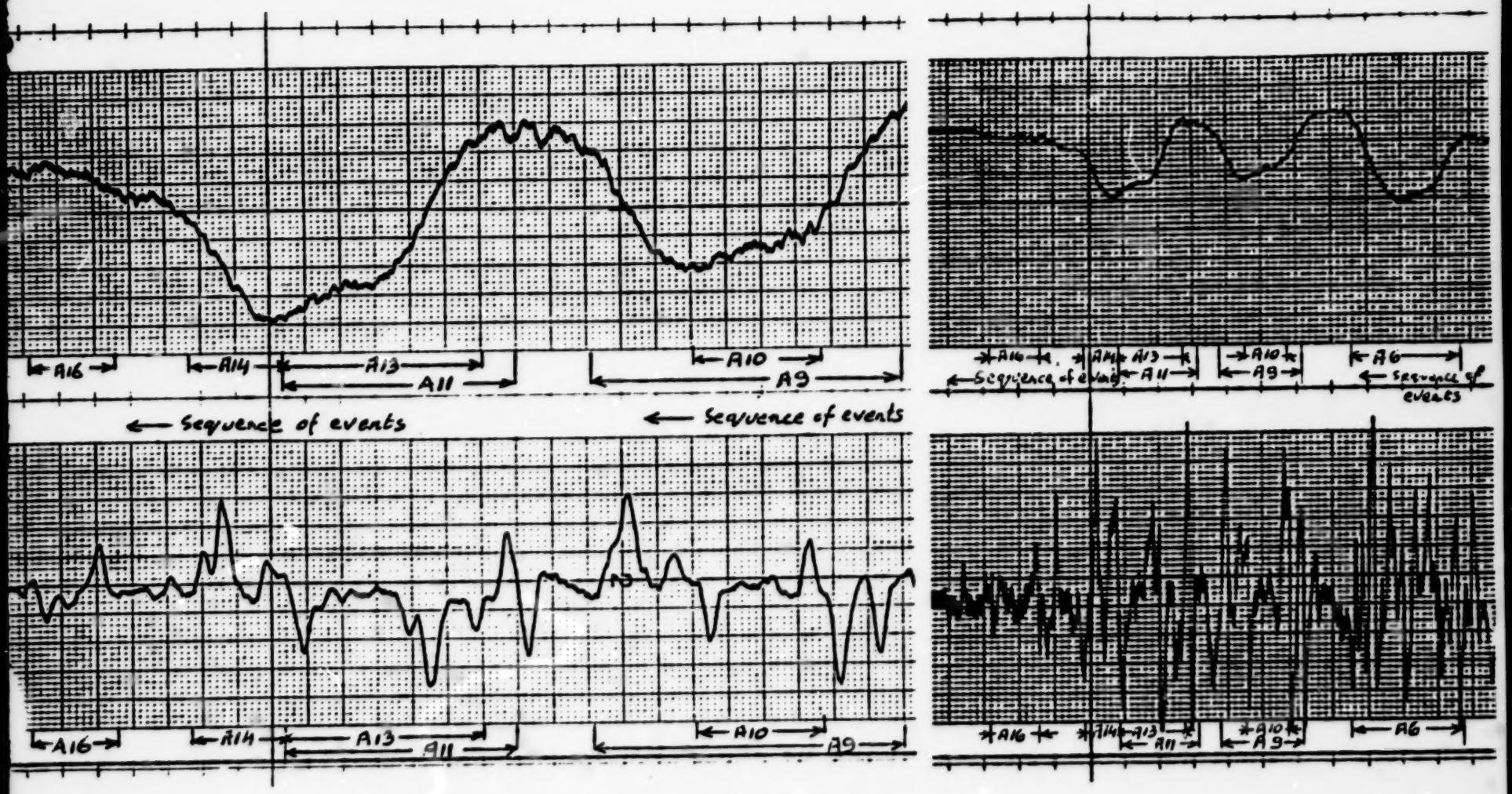


Fig. 20 — Rope 'A', (a) April, 1989, and (b) March 1990, testing with Magnograph; defects A16, A14, A13, A10, and A9

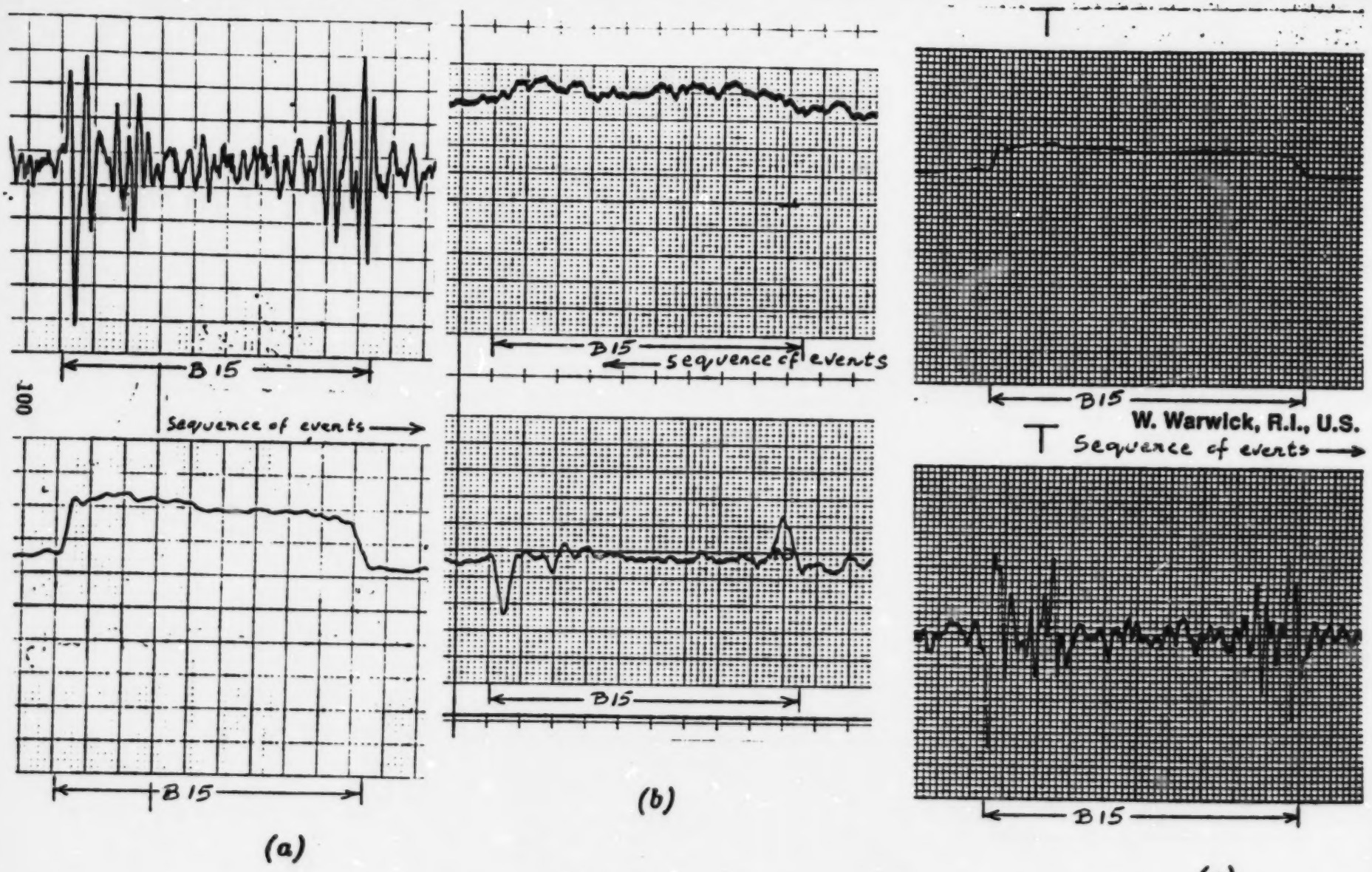


Fig. 27a — Rope 'B', April, 1989, testing with (a) Rotescograph, (b) Magnograph, and (c) LMA-250; defect B15

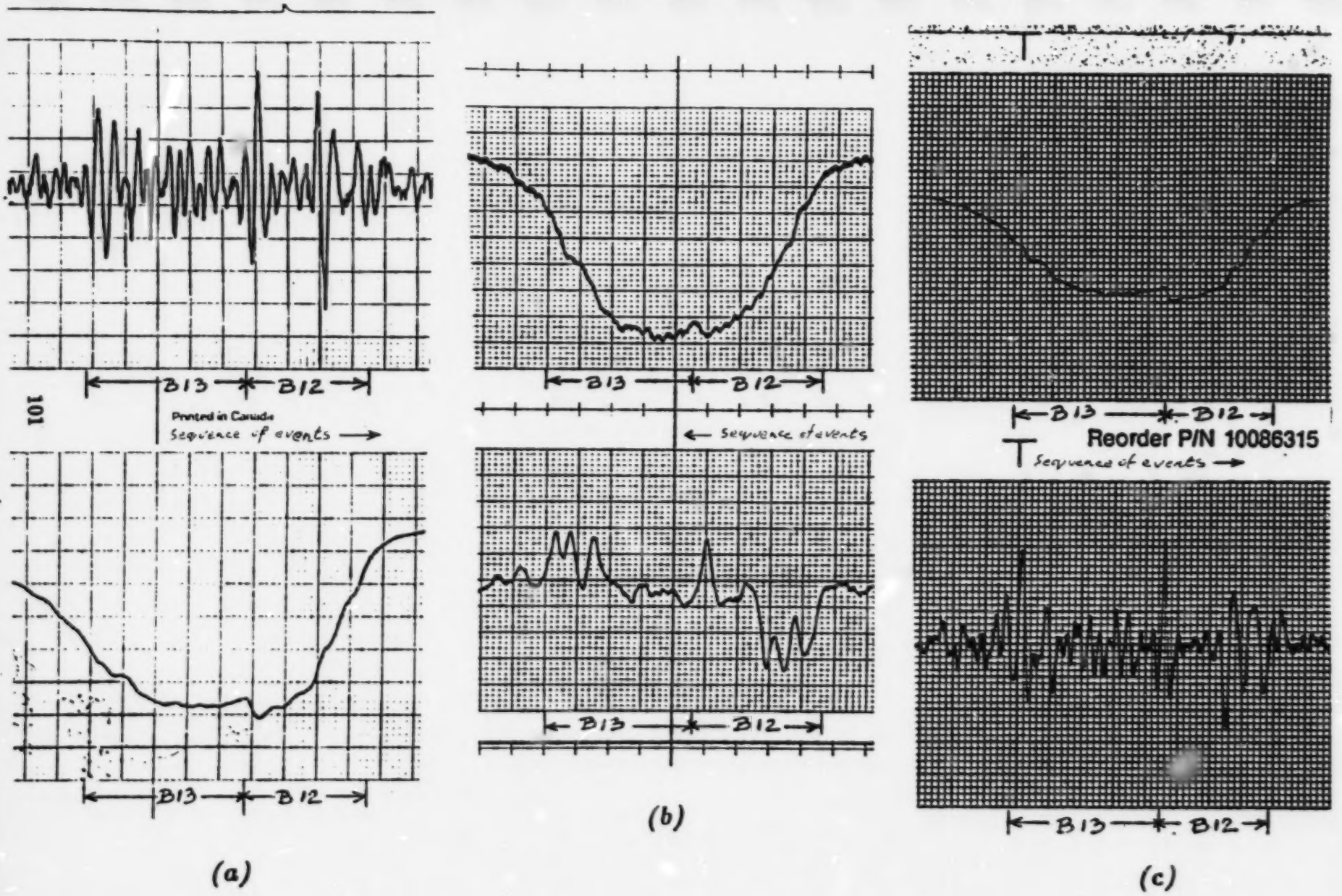


Fig. 27b — Rope 'B', April, 1989, testing with (a) Rotescograph, (b) Magnograph, and (c) LMA-250; defects B13 and B12

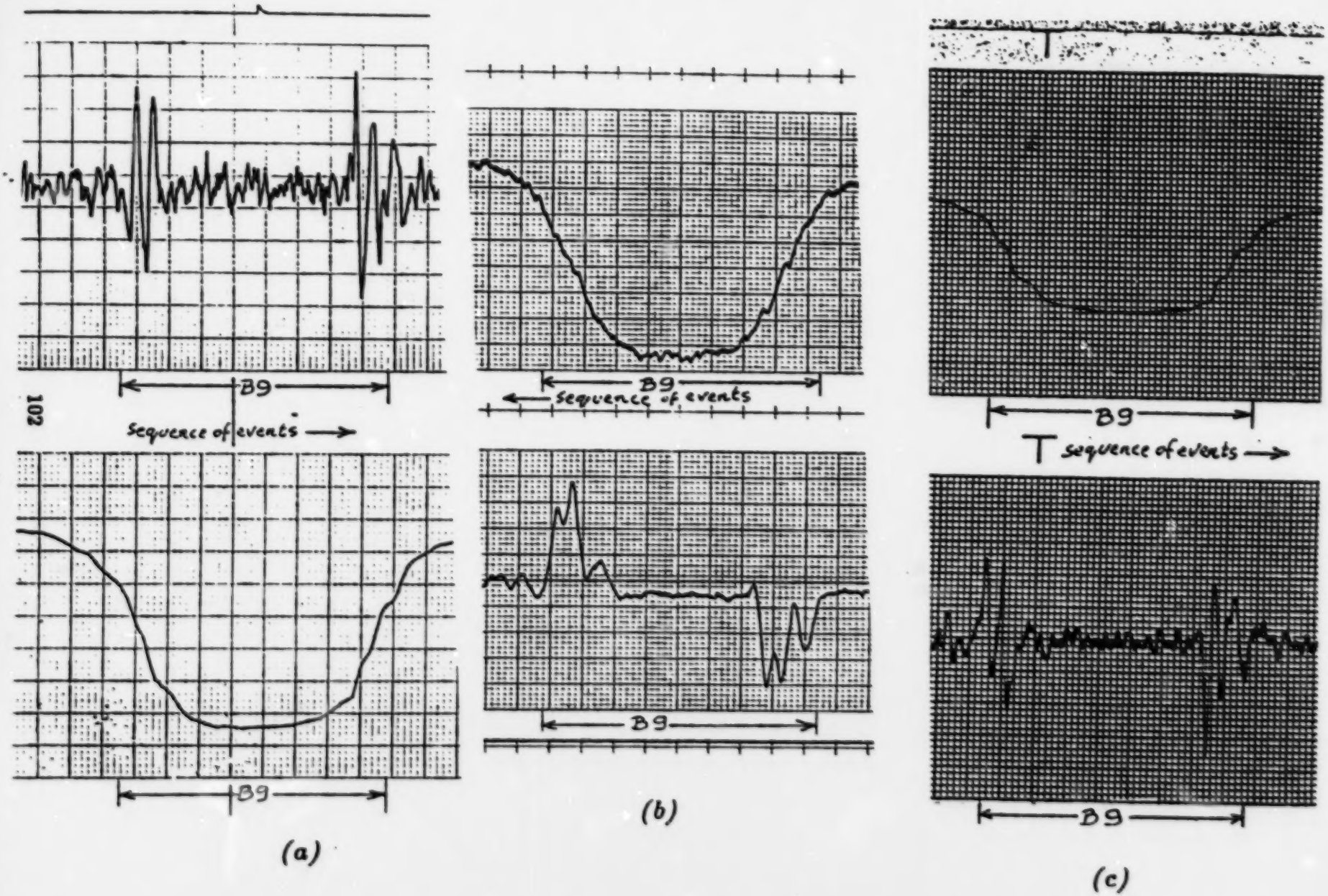


Fig. 27c — Rope 'B', April, 1989, testing with (a) Rotescograph, (b) Magnograph, and (c) LMA-250: defect B9

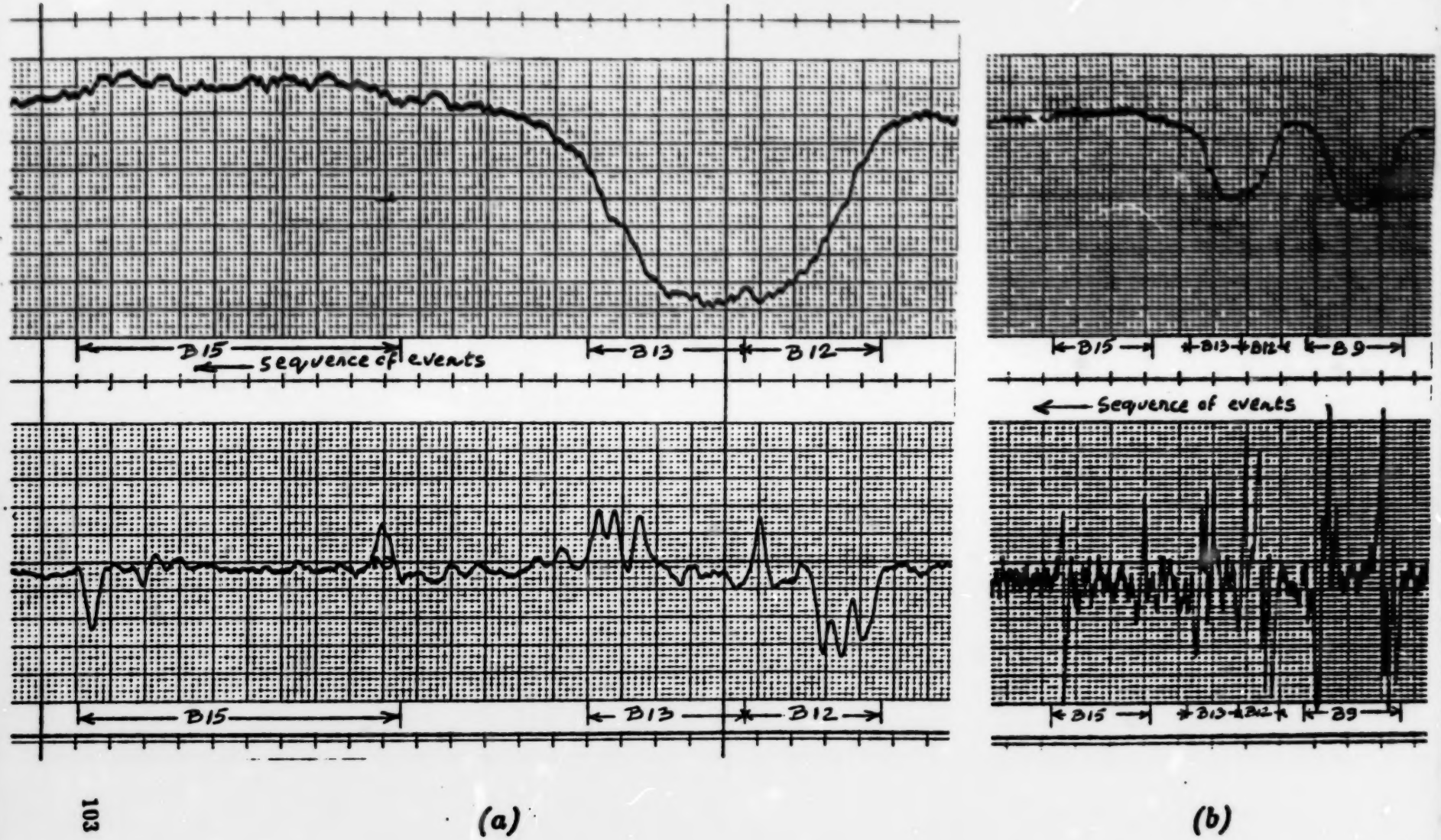


Fig. 28 — Rope 'B', (a) April, 1989, and (b) March, 1990, testing with Magnograph; defects B15, B13, and B12

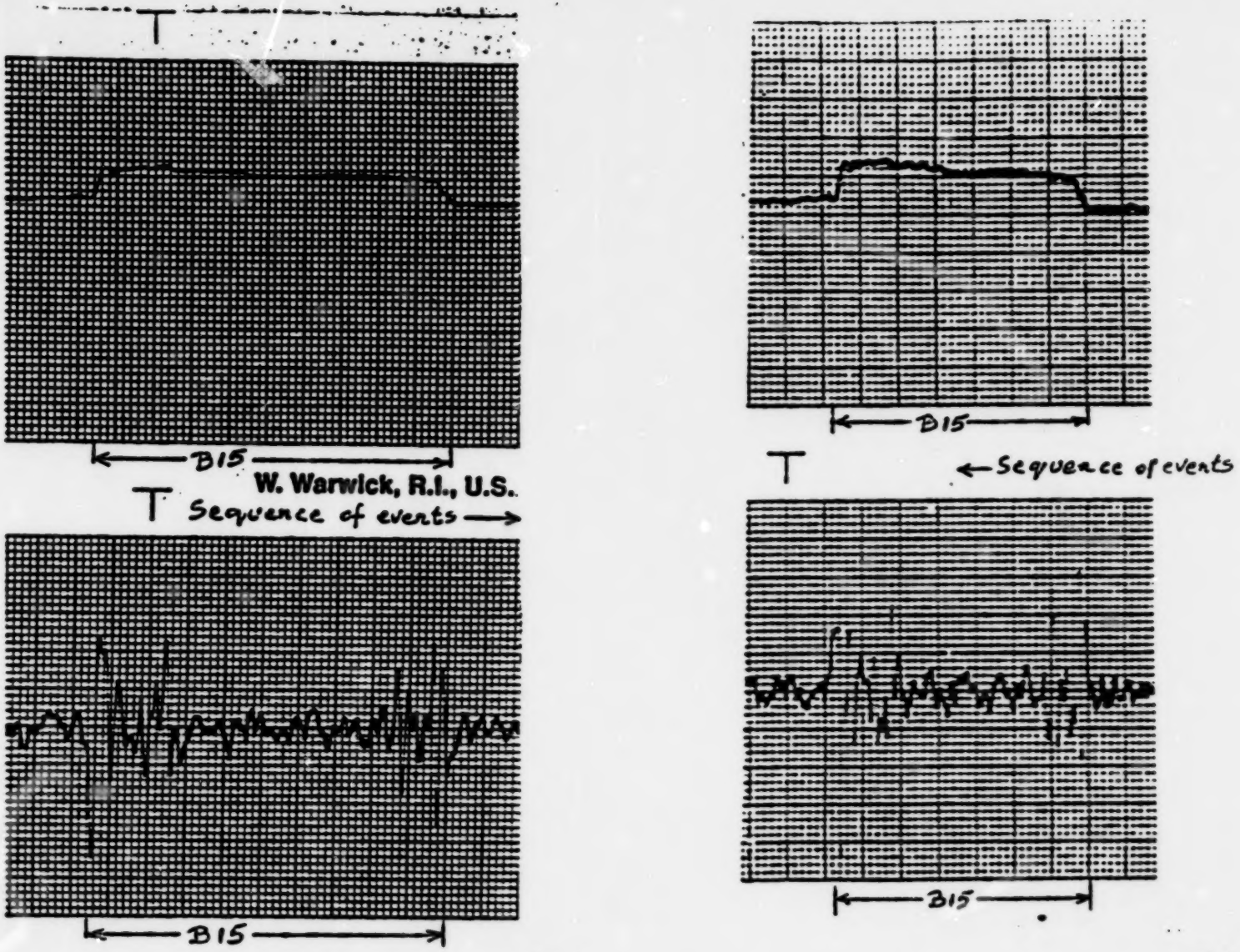


Fig. 29a — Rope 'B', (a) April, 1989, and (b) March, 1990, testing with LMA-250; defect B15

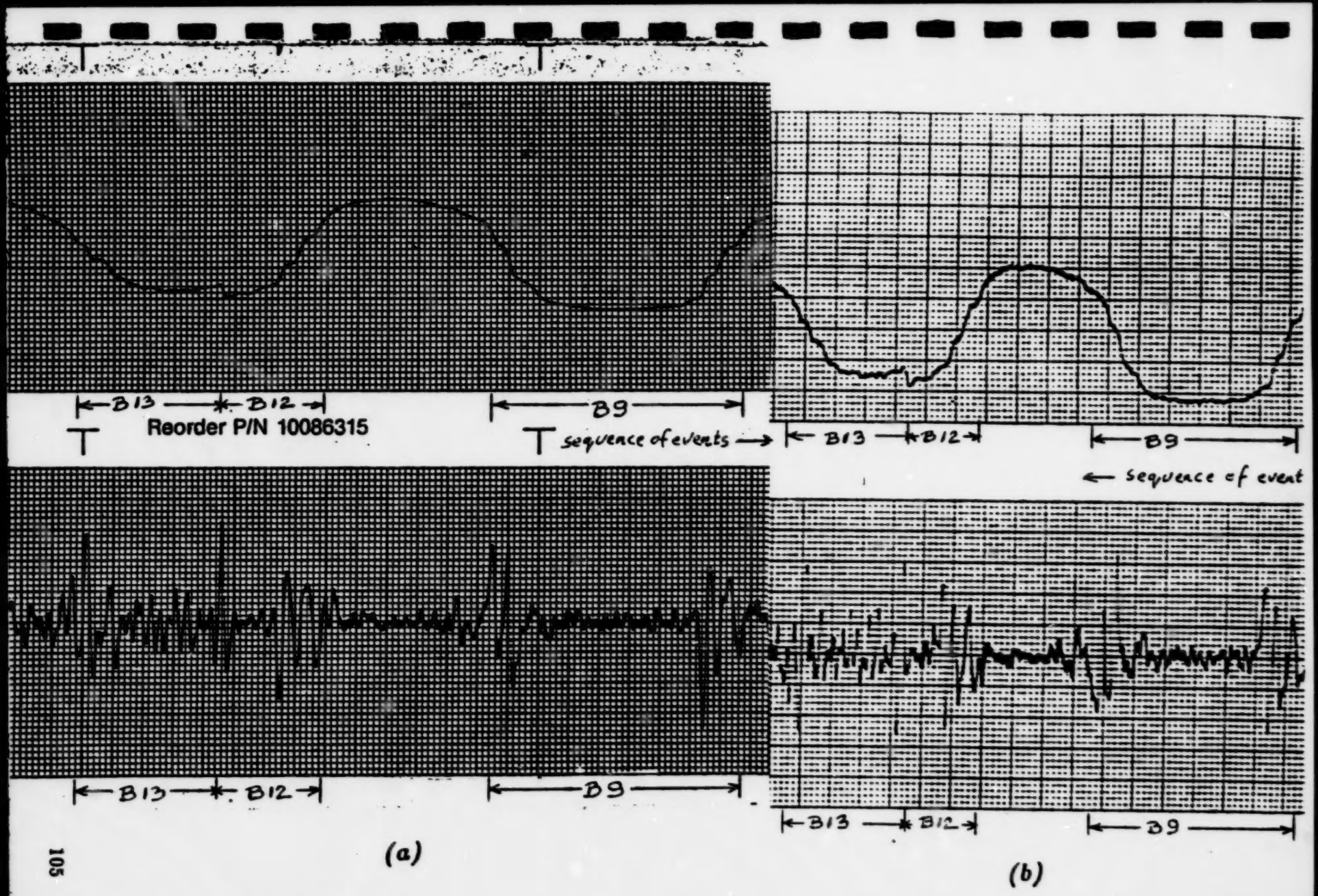


Fig. 29b — Rope 'B', (a) April, 1989, and (b) March, 1990, testing with LMA-250; defects B13, B12, and B9

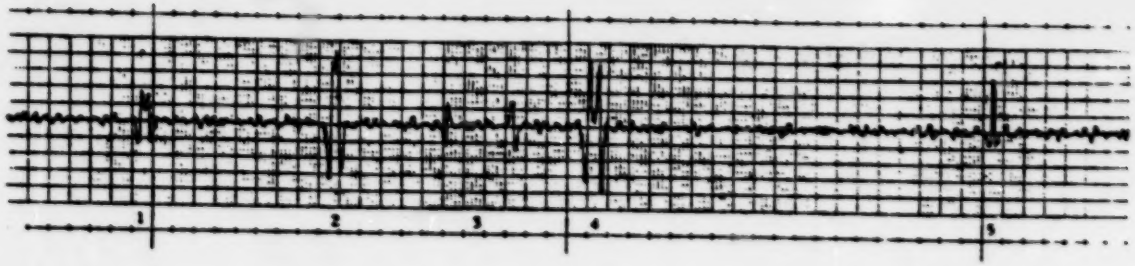


Fig. 30a — Rotescograph; LF trace with broken wires (various diam and gaps)

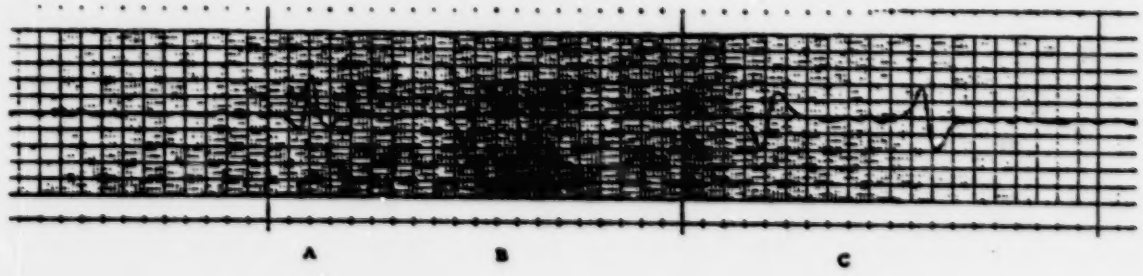


Fig. 30b — Rotescograph; LF trace with increasing wire-gap lengths

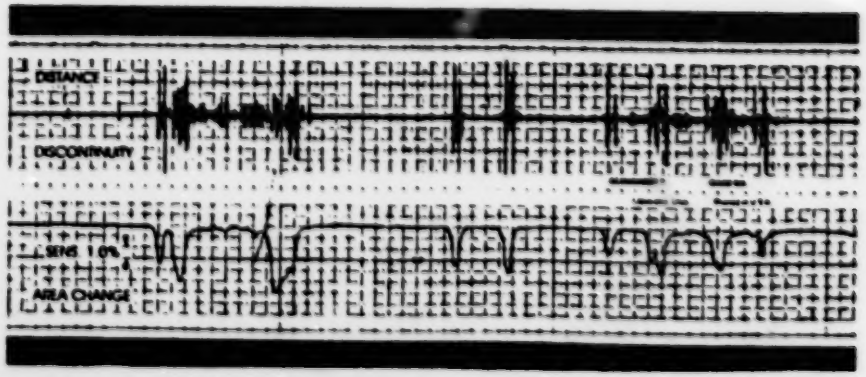


Fig. 30c — Rotescograph; LMA and LF traces with localised rope defects

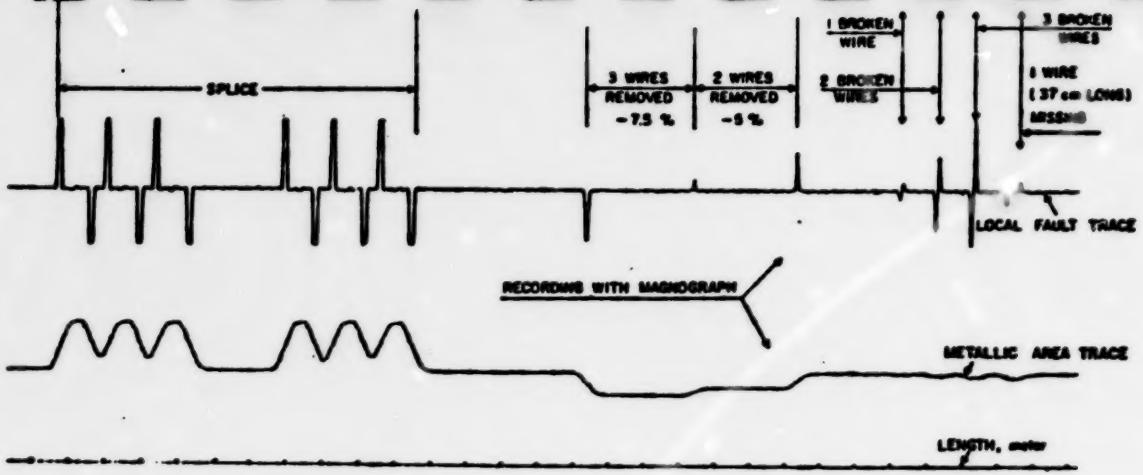


Fig. 31 — Magnograph; LMA and LF instrument traces

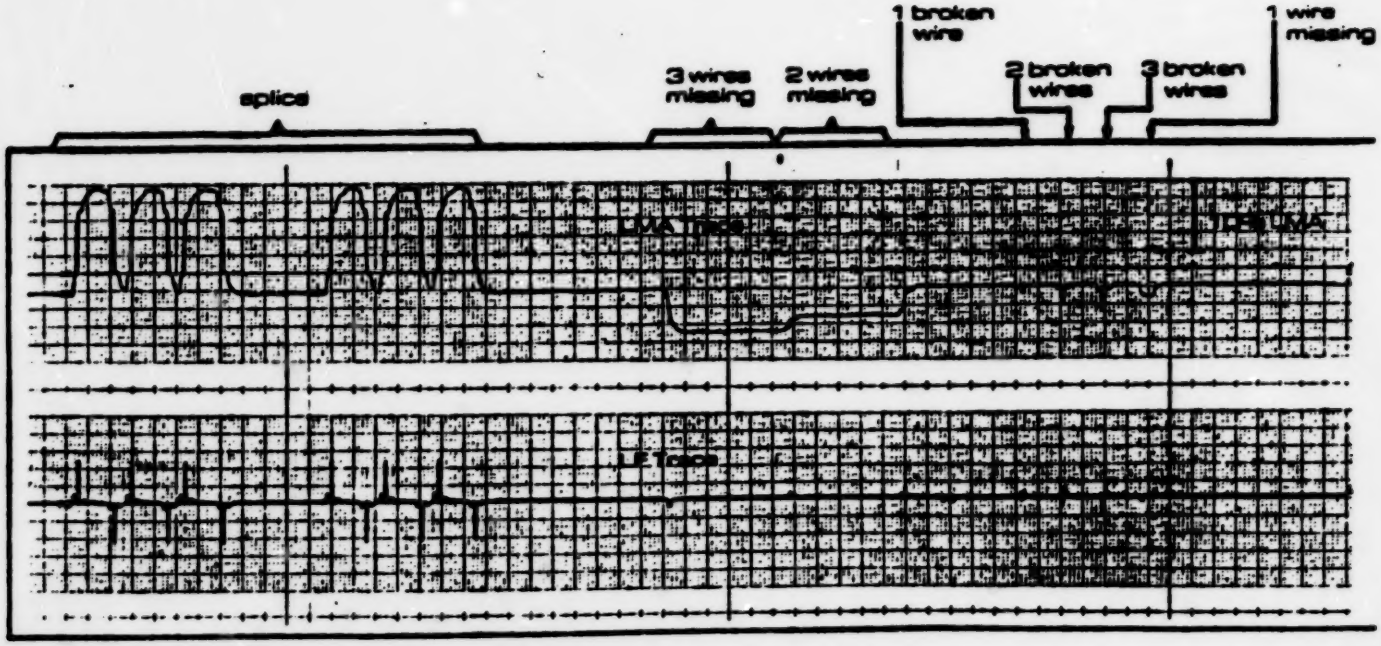


Fig. 32 — LMA-250; LMA and LF instrument traces

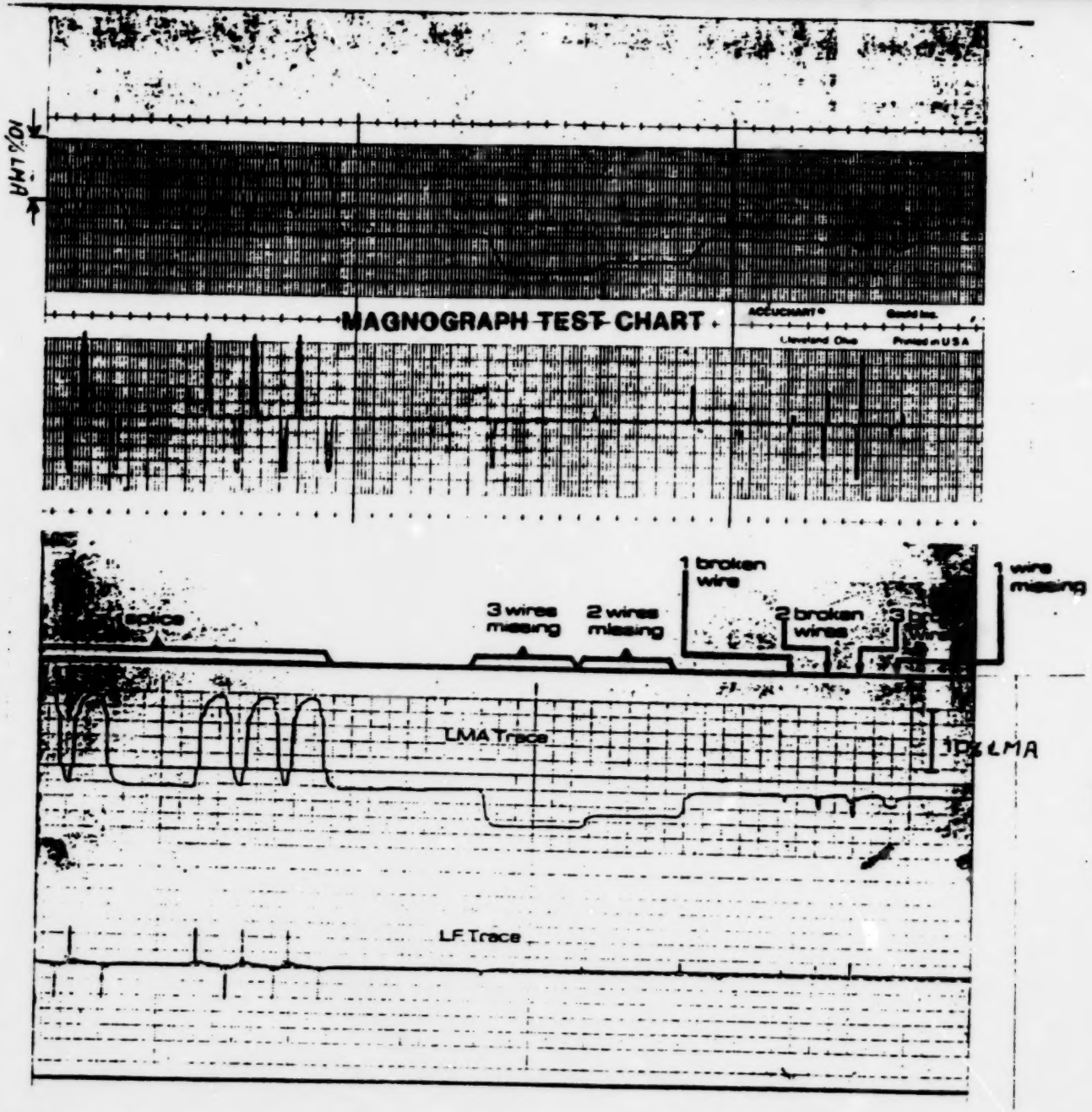
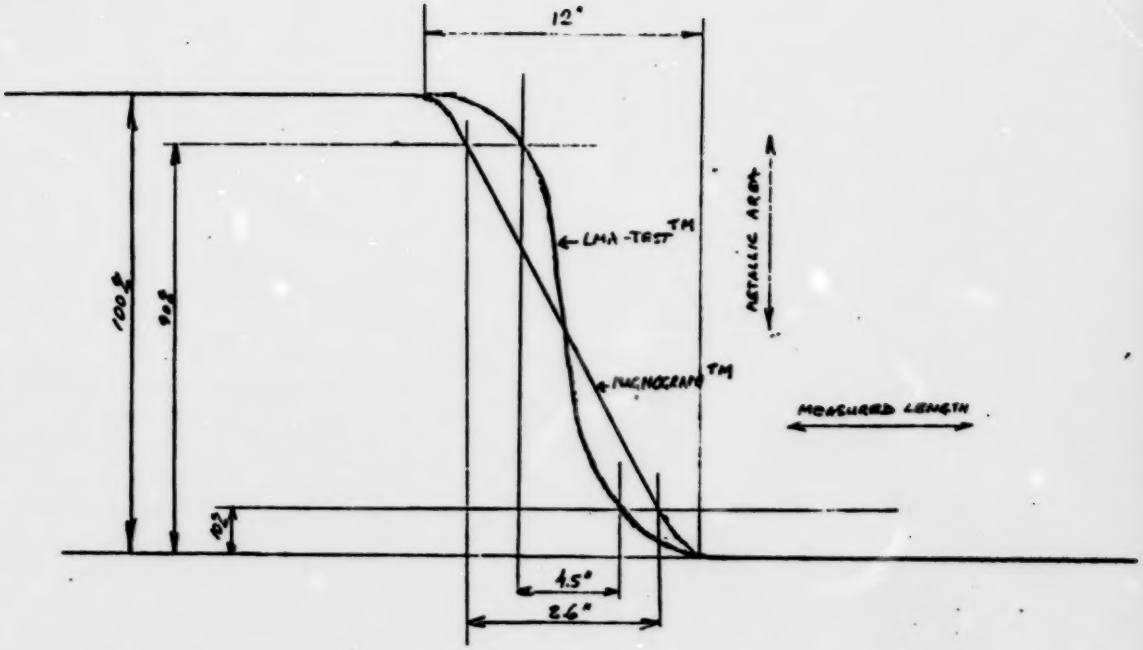


Fig. 32a — Performance comparison, on a 19 mm diam stranded wire-rope, of the: (a) Magnograph, and (b) LMA-series instruments

Fig. 32b — Step-response comparison between the LMA-series and the Magnograph instruments



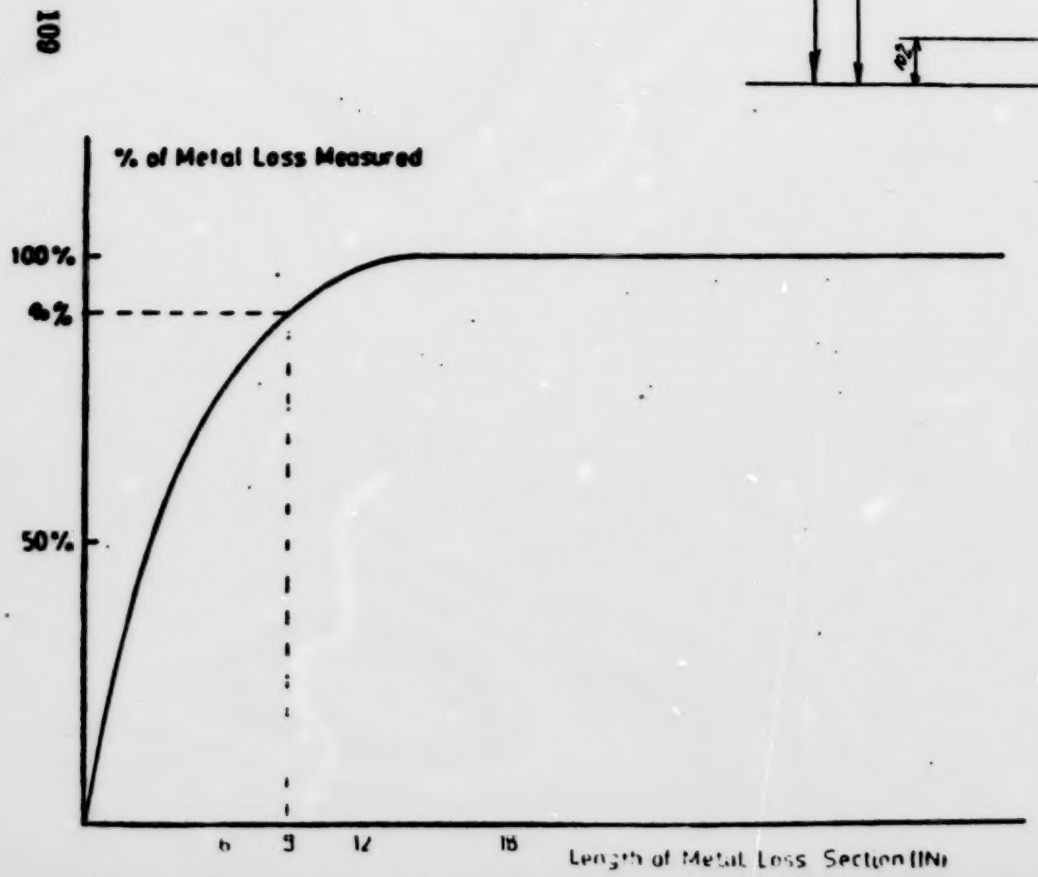
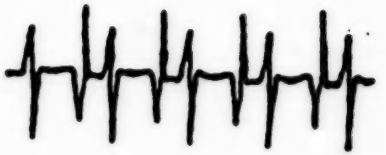


Fig. 32c — Percentage of actual metal loss, measured by the Magnograph as a function of rope-defect length

(a)

(c)

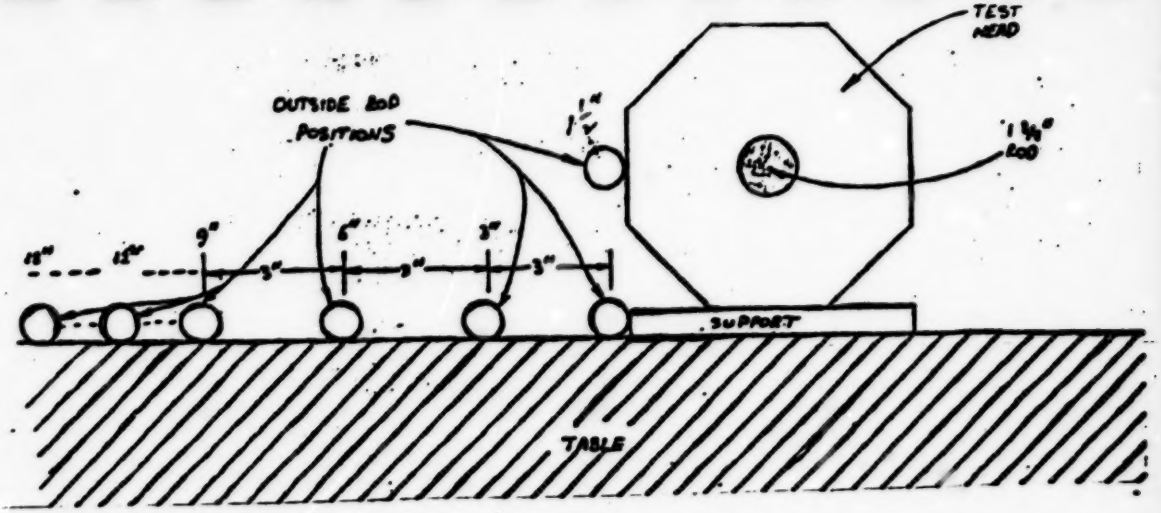
(b)



(d)

Fig. 33 — LF traces of (a) LMA-250, (b) Rotescograph, (c) Magnograph and (d) WBK instruments

(a) test set-up,



(b) test-results

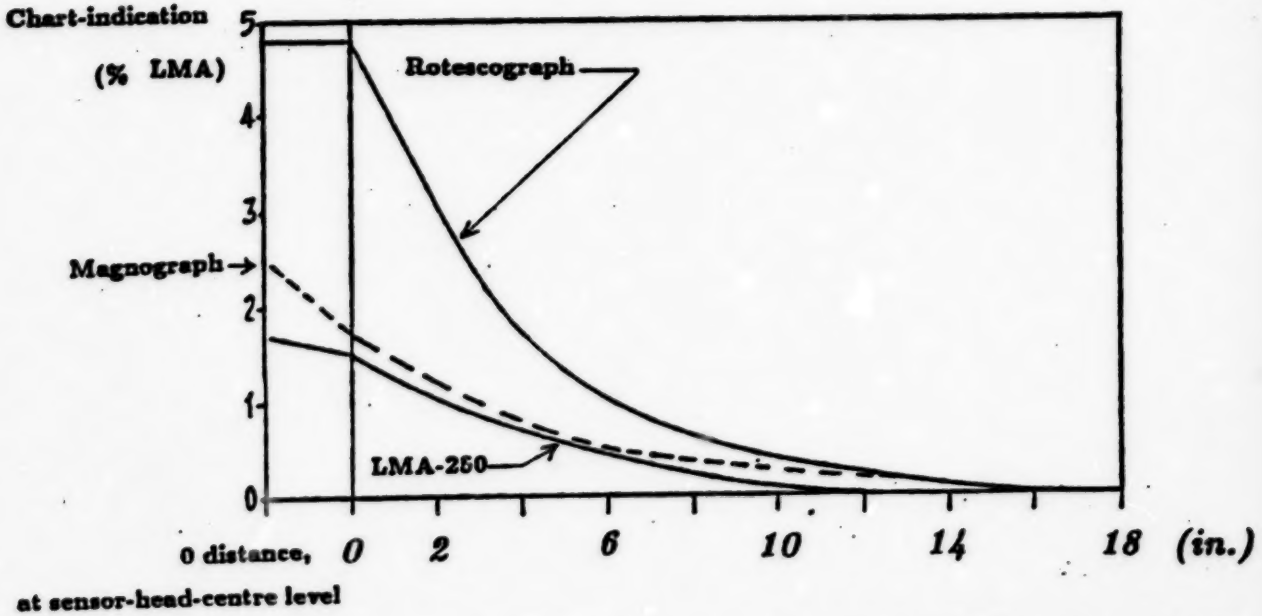


Fig. 34 — Influence of external, stationary, ferromagnetic bodies on the LMA instrument trace

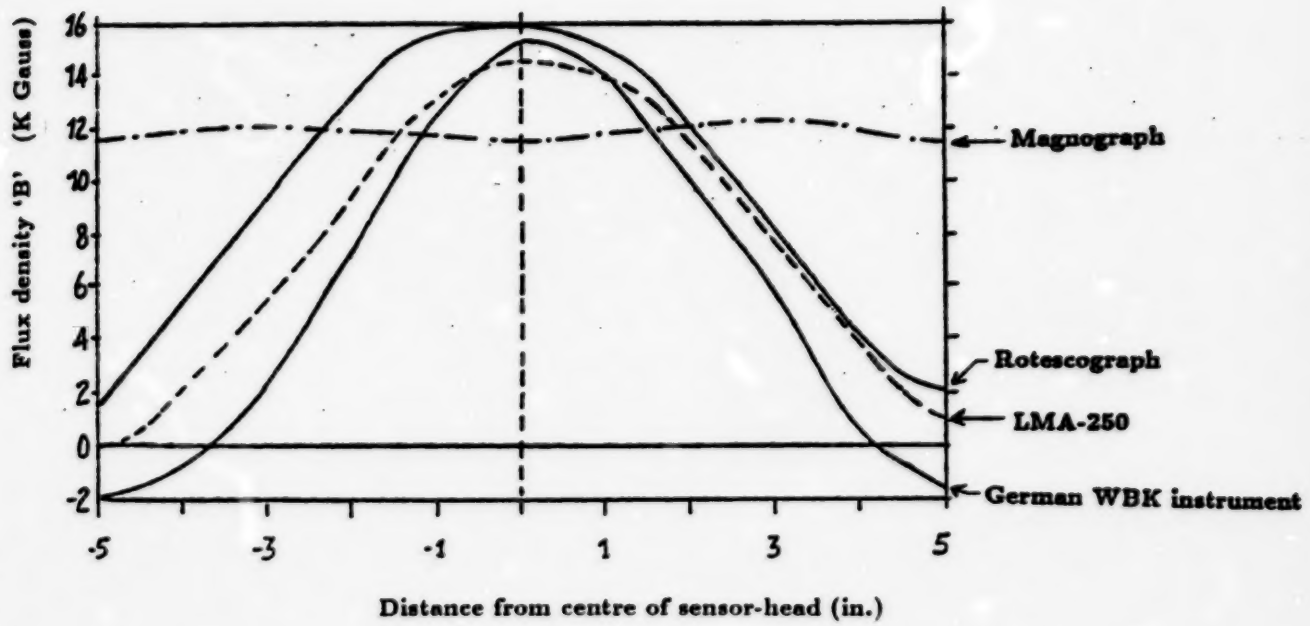


Fig. 35 — Flux-density distribution in sensor-heads

APPENDIX 4

Test procedure — a pictorial record
Figures 36 to 55

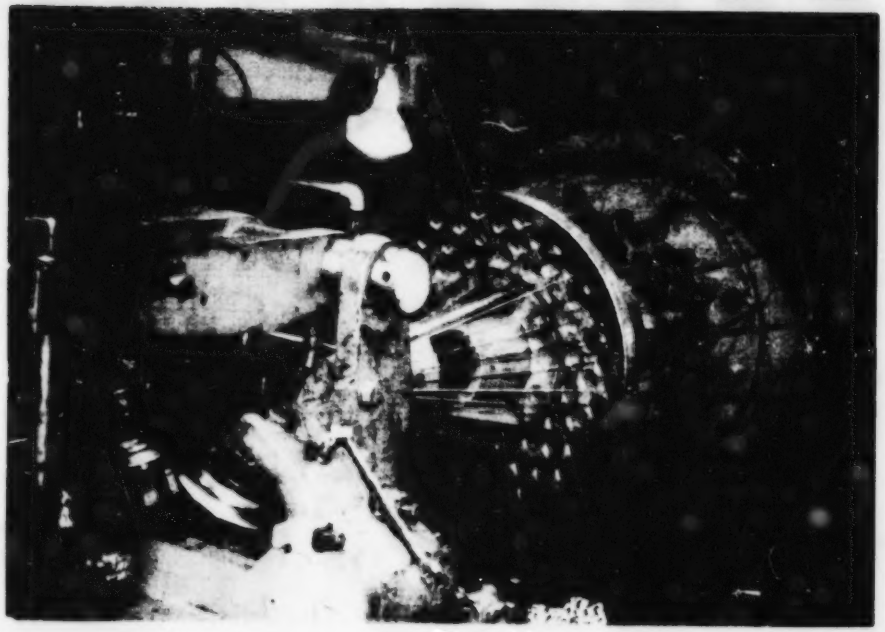


Fig. 36 — Rope fabrication

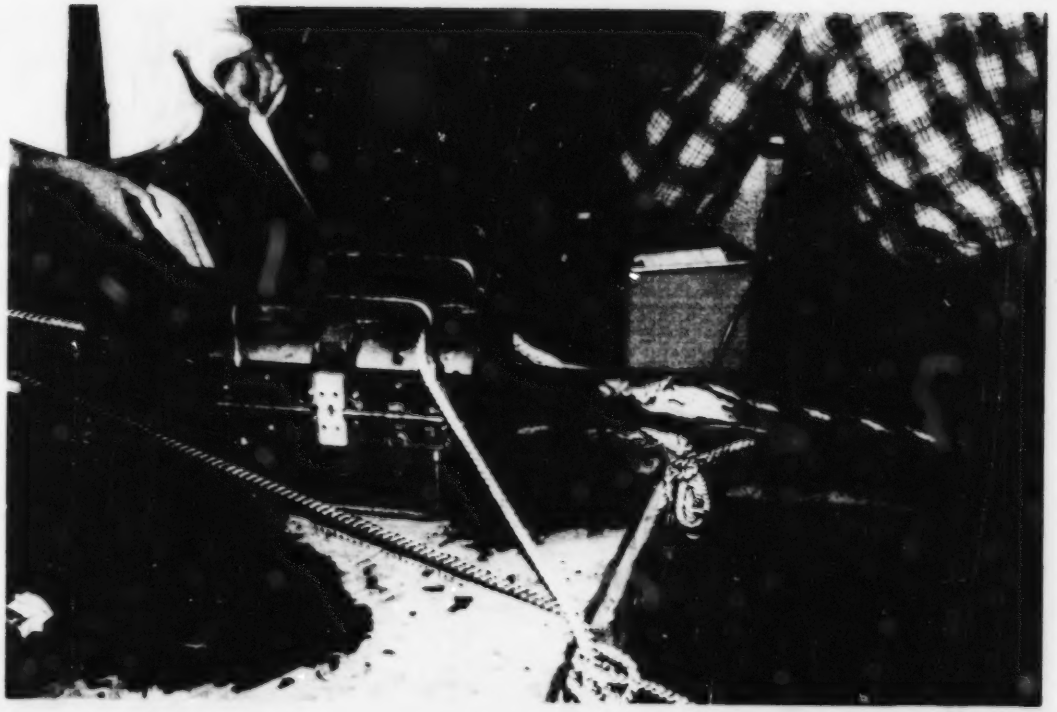


Fig. 37 — LMA-250 sensor-head,

with pile of scraped-off rope corrosion products

Fig. 38 — Lead-cable pulling test-rope onto take-up reel

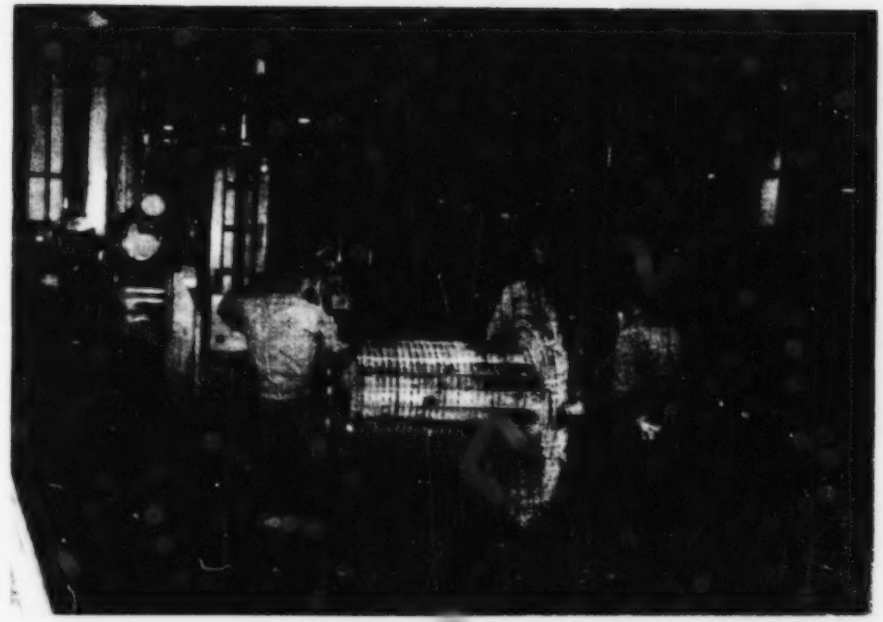


Fig. 39 — Mounting of take-up reel on rope-winder

Fig. 40 — Testing in progress with, right-to-left:

LMA-250 (first), Rotescograph (second),

Magnograph (third) along rope

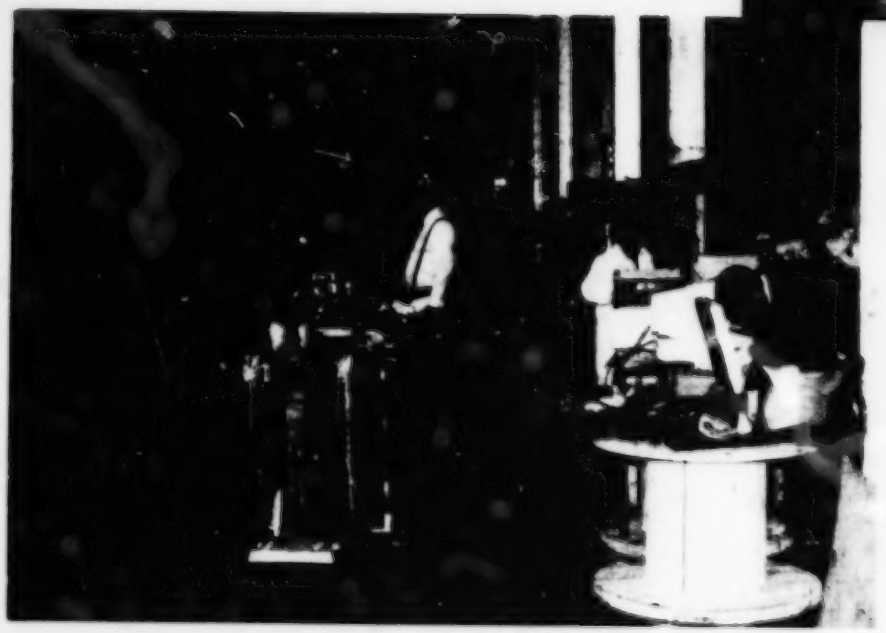


Fig. 41 — As Fig. 40, viewed from rope inlet end

(note small diam lead-cable linking test-ropes)

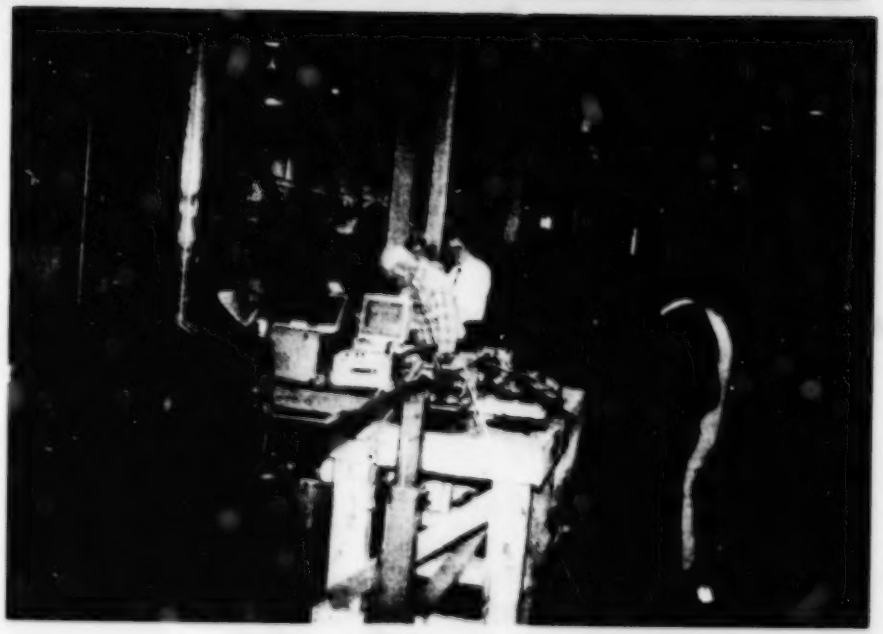


Fig. 42 — As Fig. 40, viewed from rope outlet end

Fig. 43 — Testing in progress, viewed from rope inlet end

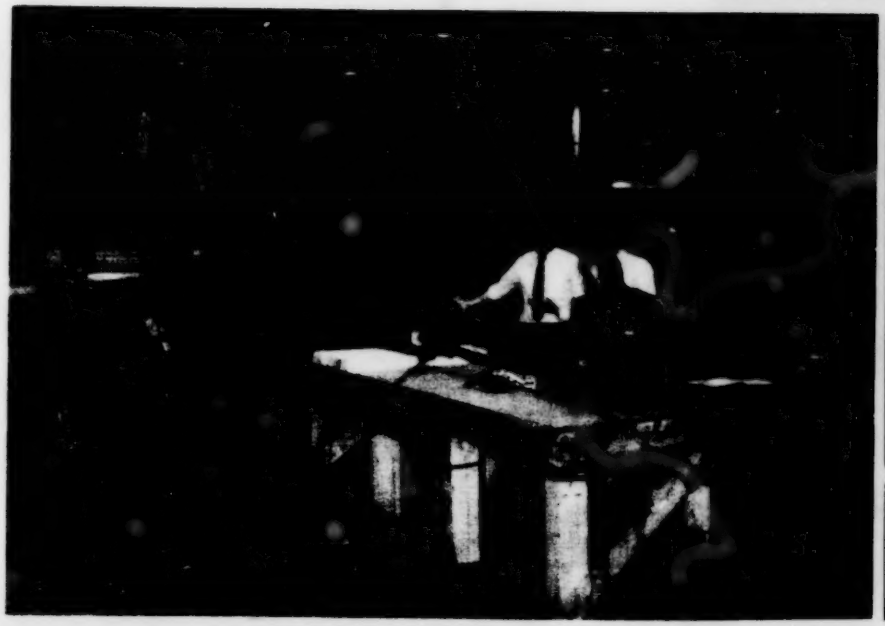


Fig. 44 — testing in progress, with LMA-250 (first) and Magnograph (second) along rope, right-to-left

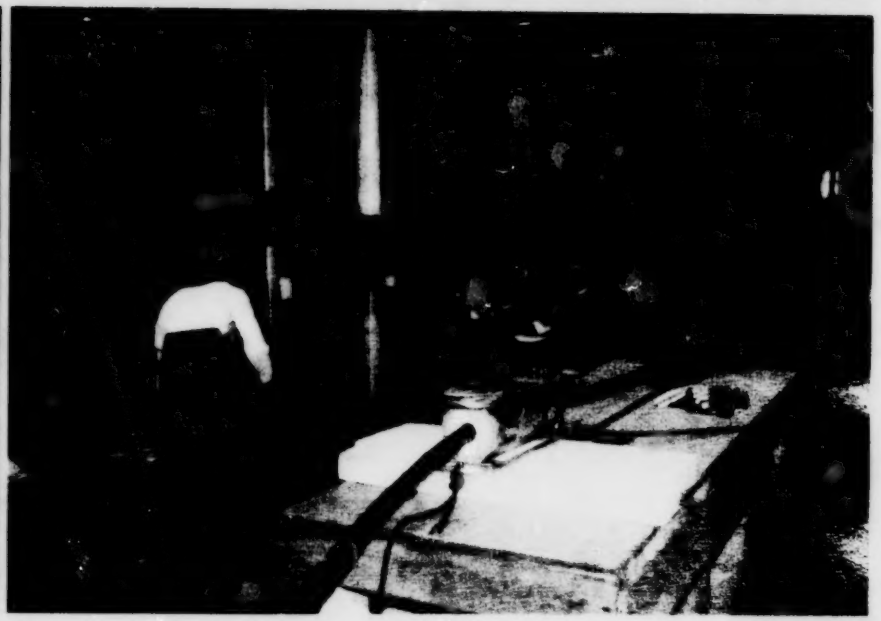


Fig. 45 — As Fig. 42, but viewed from rope outlet end

Fig. 46 — Electronic control and recorder-sections of LMA-250 and of Magnograph. Also display screen of digitized data

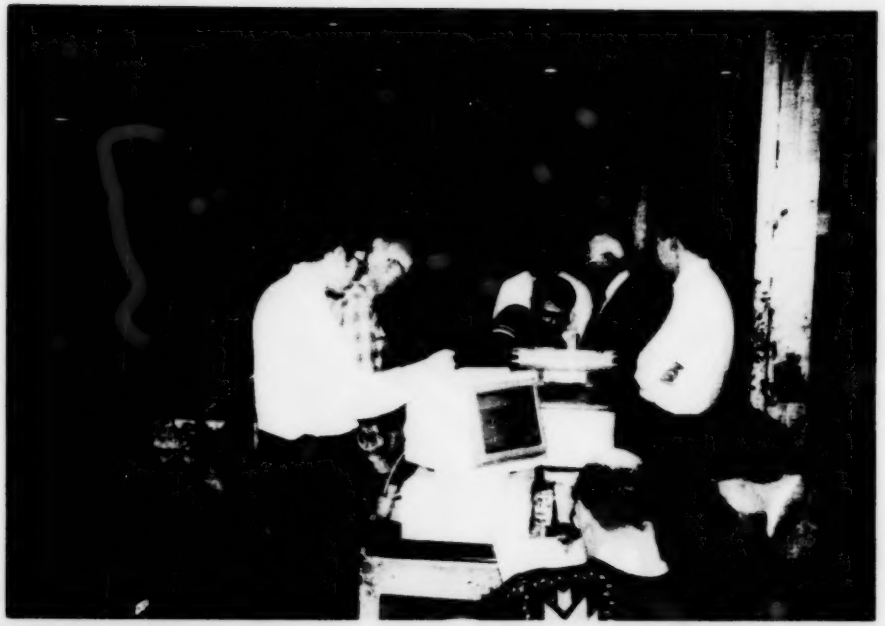


Fig. 47 — As Fig. 43, another view

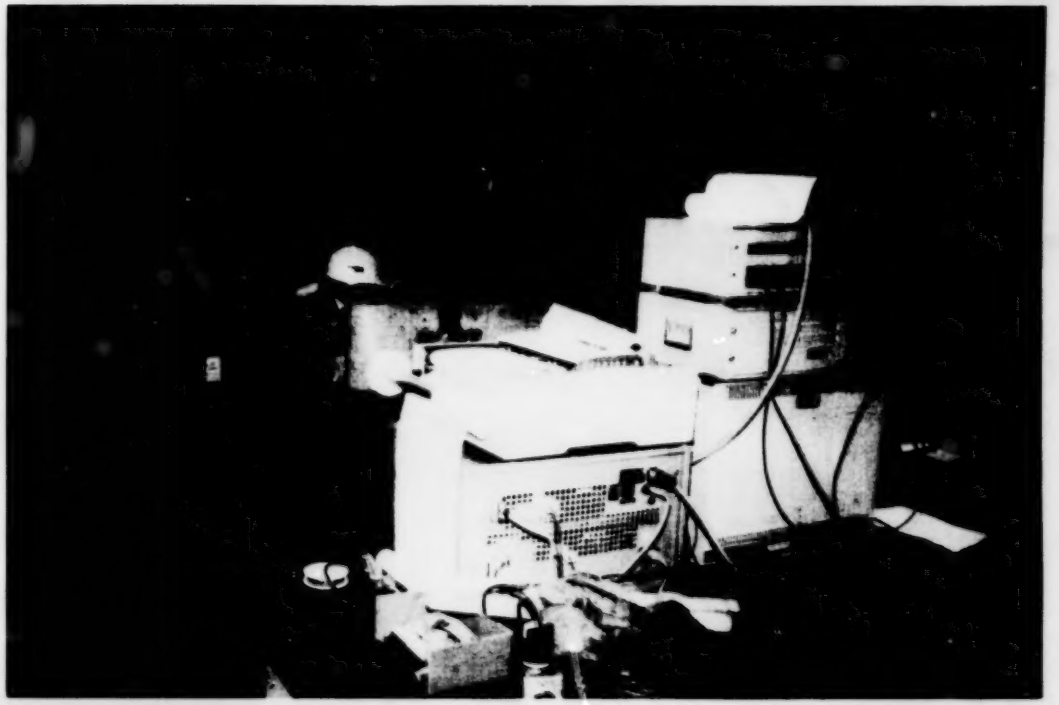


Fig. 48 — Electronic control and recorder-sections of German WBK instrument

Fig. 49 — As Fig. 48, another view

Fig. 50 — Sensor-head of LMA-250

Fig. 51 — Sensor-head of Magnograph

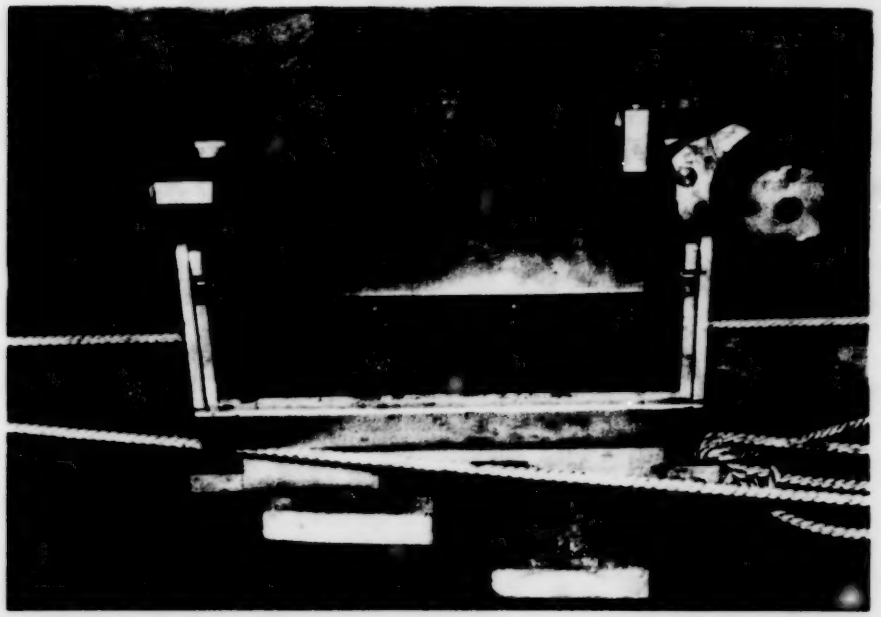


Fig. 52 — Sensor-head of Rotescograph

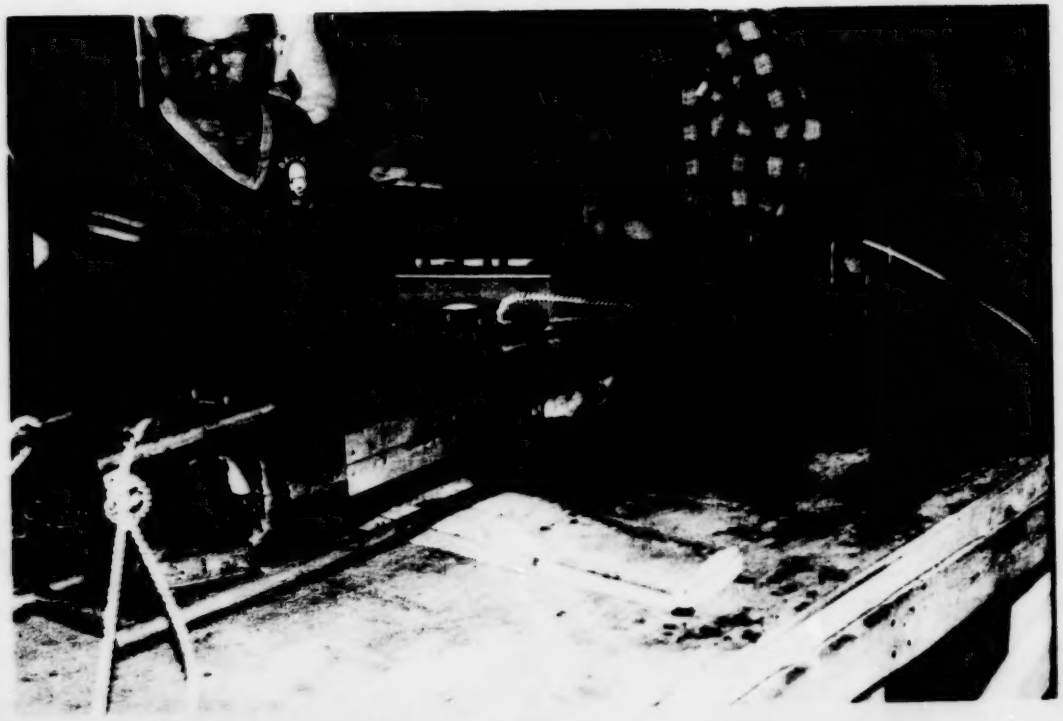


Fig. 53 — Close-up view of test process with Magnograph (in foreground) and LMA-250

Fig. 54 — Close up of open Magnograph sensor-head

(note pile of corrosion products)

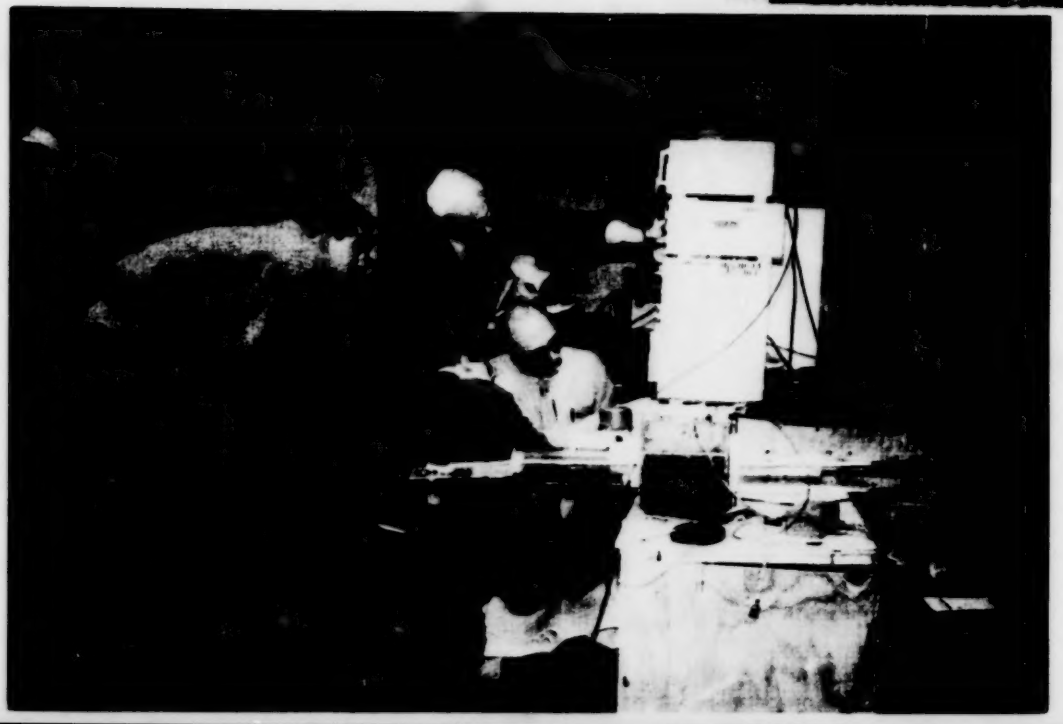


Fig. 55 — Testing LF chart-trace

of German WBK instrument